

VOC CONTROL DEVICES/ SCRUBBERS

Compliance Assistance Program
California Environmental Protection Agency
Air Resources Board

May 1995



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Table of Contents

100 INTRODUCTION

| | |
|--|----------|
| 101 AIR RESOURCES BOARD | 100 - 1 |
| 102 COMPLIANCE ASSISTANCE PROGRAM | 100 - 1 |
| 102.1 Target Audience | 100 - 3 |
| 103 MANUAL SCOPE AND ORGANIZATION | 100 - 4 |
| 104 MAINTENANCE OF MANUAL | 100 - 4 |
| 105 VOC HEALTH CONCERNS | 100 - 4 |
| 105.1 Ozone | 100 - 5 |
| 105.2 VOC | 100 - 5 |
| 105.2.1 Sources of VOCs and Hydrocarbons | 100 - 6 |
| 106 AIR POLLUTION CAPTURE SYSTEMS | 100 - 7 |
| 106.1 Hoods | 100 - 7 |
| 106.2 Fans/blowers | 100 - 9 |
| 106.2.1 Axial Fans | 100 - 11 |
| 106.2.2 Centrifugal Fans | 100 - 12 |
| 106.2.3 Fan Blade Types | 100 - 13 |
| 106.2.4 Fan System Principles | 100 - 14 |
| 106.2.5 Standard and Actual Conditions | 100 - 18 |
| 107 REGULATIONS | 100 - 20 |
| 107.1 Federal Regulations | 100 - 20 |
| 107.2 State Regulations | 100 - 21 |
| 107.3 Local (District) Regulations | 100 - 22 |
| 107.3.1 Equipment Breakdown Provisions | 100 - 23 |
| 107.4.1 Variances | 100 - 25 |

200 ADSORPTION

| | |
|--|----------|
| 201 BASIC PRINCIPLES | 200 - 1 |
| 201.1 Physical Adsorption | 200 - 1 |
| 201.2 Chemical Adsorption | 200 - 4 |
| 202 MATERIALS USED AS ADSORBENTS | 200 - 4 |
| 203 ACTIVATED CARBON PRODUCTION | 200 - 5 |
| 203.1 Carbonization | 200 - 5 |
| 204 CARBON POROSITY | 200 - 6 |
| 205 THE CARBON ADSORPTION PROCESS | 200 - 8 |
| 205.1 The Outlet Concentration Curve | 200 - 15 |
| 206 REGENERATION OF CARBON BEDS | 200 - 16 |
| 207 CARBON ADSORPTION SYSTEM DESIGN CONSIDERATIONS | 200 - 18 |
| 208 FACTORS AFFECTING ADSORPTION EFFICIENCY & WORKING CAPACITY | 200 - 24 |
| 208.1 Temperature | 200 - 24 |
| 208.2 Relative Humidity | 200 - 25 |
| 208.3 Concentration, Type of VOC and Impurities | 200 - 27 |
| 208.4 Fouling | 200 - 29 |
| 208.5 Volumetric Flow Rate | 200 - 29 |

| | |
|---|----------|
| 208.6 Channeling | 200 - 29 |
| 208.7 Regeneration | 200 - 30 |
| 209 MAIN TYPES OF CARBON ADSORPTION SYSTEMS | 200 - 30 |
| 209.1 Open Carbon Adsorption Systems | 200 - 31 |
| 209.2 Closed Carbon Adsorption Systems | 200 - 31 |
| 209.3 Moving Bed and Fixed Bed Systems | 200 - 32 |
| 210 BULK PLANT ADSORBER AND ABSORBER | 200 - 34 |
| 211 ADSORBER SYSTEM WITH STEAM REGENERATION | 200 - 36 |
| 212 CALCULATIONS | 200 - 36 |
| 212.1 Example Calculation | 200 - 38 |
| 213 RULE DISCUSSION | 200 - 40 |
| 213.1 District Regulations | 200 - 40 |
| 213.2 Permits | 200 - 43 |
| 214 INSPECTION INTRODUCTION | 200 - 44 |
| 214.1 Sequence of Inspection | 200 - 46 |
| 214.1.1 Co-Current Approach | 200 - 46 |
| 214.1.2 Counter-Flow Approach | 200 - 46 |
| 214.1.3 Other Approaches | 200 - 46 |
| 214.2 Levels of Inspection | 200 - 47 |
| 215 PRE-INSPECTION PROCEDURES | 200 - 47 |
| 215.1 File Review | 200 - 47 |
| 215.2 Regulation Review | 200 - 48 |
| 215.3 Equipment Check | 200 - 48 |
| 215.4 Pre-entry and Entry | 200 - 48 |
| 215.5 Pre-inspection Meeting | 200 - 49 |
| 216 CARBON ADSORPTION SYSTEM INSPECTION | 200 - 49 |
| 216.1 Adsorber Shell and Duct System | 200 - 49 |
| 216.2 VOC Continuous Emission Monitors | 200 - 50 |
| 216.2.1 Level 3 and 4 Inspections | 200 - 50 |
| 216.3 Static Pressure and Temperature | 200 - 51 |
| 216.4 Adsorption/Desorption Cycles | 200 - 51 |
| 216.5 Solvent Use | 200 - 51 |
| 217 POST-INSPECTION PROCEDURES | 200 - 54 |
| 300 ABSORPTION | |
| 301 INTRODUCTION | 300 - 1 |
| 302 THE ABSORPTION PROCESS | 300 - 2 |
| 302.1 Factors Promoting Absorption | 300 - 2 |
| 303 ABSORBER DESIGN | 300 - 3 |
| 303.1 Packed Columns | 300 - 5 |
| 303.2 Plate Columns | 300 - 13 |
| 303.2.1 Plate Column Design | 300 - 13 |
| 304 PACKED COLUMN CALCULATIONS | 300 - 15 |
| 305 PLATE COLUMN CALCULATIONS | 300 - 16 |
| 306 PACKED COLUMN VS PLATE COLUMN | 300 - 18 |

400 CONDENSATION

| | |
|--|-----------------|
| 401 INTRODUCTION | 400 - 1 |
| 402 EQUIPMENT USED TO CONDENSE POLLUTANTS..... | 400 - 2 |
| 402.1 Contact and Surface Condensers | 400 - 2 |
| 402.1.1 Contact Condensers | 400 - 3 |
| 402.1.2 Surface Condensers..... | 400 - 3 |
| 402.1.3 Fouling and Cleaning | 400 - 7 |
| 402.2 Refrigeration and the Phaseout of CFC..... | 400 - 8 |
| 402.2.1 New Chemical Substitutes | 400 - 10 |
| 402.3 Bulk Plant Refrigeration Vapor Recovery System..... | 400 - 11 |
| 403 BASIC HEAT EXCHANGER RELATIONSHIPS | 400 - 13 |
| 404 PROPER CONDENSER MAINTENANCE..... | 400 - 14 |
| 405 RULE DISCUSSION..... | 400 - 15 |
| 405.1 District Regulations | 400 - 16 |
| 405.2 District Permits to Operate | 400 - 22 |
| 406 INSPECTION INTRODUCTION | 400 - 24 |
| 406.1 Sequence of Inspection | 400 - 25 |
| 406.1.1 Co-Current Approach..... | 400 - 25 |
| 406.1.2 Counter-Flow Approach | 400 - 26 |
| 406.1.3 Other Approaches | 400 - 26 |
| 406.2 Levels of Inspection..... | 400 - 26 |
| 407 PRE-INSPECTION PROCEDURES..... | 400 - 27 |
| 407.1 File Review | 400 - 27 |
| 407.2 Regulation Review | 400 - 28 |
| 407.3 Equipment Check | 400 - 28 |
| 407.4 Pre-entry and Entry..... | 400 - 28 |
| 407.5 Pre-inspection Meeting | 400 - 29 |
| 408 CONDENSER SYSTEM INSPECTION | 400 - 29 |
| 408.1 Overall Condenser Condition | 400 - 29 |
| 408.2 Condenser Temperature | 400 - 30 |
| 408.3 Pressure Drop..... | 400 - 30 |
| 408.4 Continuous Emission Monitor | 400 - 30 |
| 408.5 Liquid Flow Rate | 400 - 32 |
| 408.6 Solvent Recovery/disposal System | 400 - 32 |
| 408.7 Refrigeration System | 400 - 32 |
| 409 POST-INSPECTION PROCEDURES | 400 - 32 |

500 INCINERATION

| | |
|---|-----------------|
| 501 COMBUSTION BASICS | 500 - 1 |
| 502 INCINERATION SYSTEMS | 500 - 4 |
| 502.1 THERMAL INCINERATORS..... | 500 - 5 |
| 502.1.1 Thermal Incinerator Problems | 500 - 10 |
| 502.2 Catalytic Incinerators | 500 - 11 |
| 502.2.1 Catalytic Oxidation Catalyst | 500 - 13 |
| 502.2.2 Catalyst Problems | 500 - 16 |
| 502.2.3 Factors Affecting Catalytic Incinerators | 500 - 19 |
| 502.3 Boilers, Process Heaters, and Flares..... | 500 - 19 |

| | |
|---|-----------------|
| 503 RULE DISCUSSION | 500 - 20 |
| 503.1 New Source Performance Standards | 500 - 21 |
| 503.2 District Regulations and Permits | 500 - 21 |
| 503.2.1 Air Pollution Regulations | 500 - 21 |
| 503.2.2 Permits | 500 - 24 |
| 504 INSPECTION INTRODUCTION | 500 - 25 |
| 504.1 Sequence of Inspection | 500 - 27 |
| 504.1.1 Co-Current Approach | 500 - 27 |
| 504.1.2 Counter-Flow Approach | 500 - 27 |
| 504.1.3 Other Approaches | 500 - 28 |
| 504.2 Levels of Inspection | 500 - 28 |
| 505 PRE-INSPECTION PROCEDURES | 500 - 28 |
| 505.1 File Review | 500 - 29 |
| 505.2 Regulation Review | 500 - 29 |
| 505.3 Equipment Check | 500 - 29 |
| 505.4 Pre-entry and Entry | 500 - 30 |
| 505.5 Pre-inspection Meeting | 500 - 30 |
| 506 INCINERATOR INSPECTION | 500 - 31 |
| 506.1 Visible Emissions | 500 - 31 |
| 506.2 Incinerator Bypass Stack | 500 - 31 |
| 506.3 Incinerator Shell and Ductwork | 500 - 31 |
| 506.4 Incinerator Operating Temperature | 500 - 32 |
| 506.5 Fan Motor Current and Static Pressure | 500 - 32 |
| 506.6 Process Evaluation | 500 - 32 |
| 506.7 VOC Outlet Concentration | 500 - 34 |
| 506.8 Measuring the Outlet Temperature (Level 3 and 4) | 500 - 34 |
| 507 POST-INSPECTION PROCEDURES | 500 - 35 |
| 600 SCRUBBERS | |
| 601 INTRODUCTION | 600 - 1 |
| 601.1 Health Effects of Particulate Matter | 600 - 1 |
| 601.2 Sources of Particulate Matter | 600 - 2 |
| 602 PARTICULATE CHARACTERISTICS AND FORMATION MECHANISMS | 600 - 4 |
| 602.1 Particle Size | 600 - 4 |
| 602.2 Particle Shapes | 600 - 5 |
| 602.3 Particle Formation | 600 - 8 |
| 603 PARTICULATE COLLECTION MECHANISMS | 600 - 10 |
| 603.1 Inertial Impaction | 600 - 11 |
| 603.2 Interception | 600 - 13 |
| 603.3 Brownian Displacement | 600 - 13 |
| 603.4 Electrostatic Attraction | 600 - 14 |
| 603.5 Gravitational Settling | 600 - 15 |
| 603.6 Thermophoresis | 600 - 15 |
| 603.7 Diffusiophoresis | 600 - 16 |
| 603.8 Other Collection Mechanisms | 600 - 16 |
| 604 LIQUID-TO-GAS RATIO | 600 - 17 |
| 605 TYPES OF WET SCRUBBER DESIGNS | 600 - 17 |

| | | |
|---------|---|----------|
| 605.1 | Spray Chambers | 600 - 18 |
| 605.2 | Spray Towers | 600 - 19 |
| 605.3 | Wet Dynamic/Mechanically-Aided Scrubbers | 600 - 21 |
| 605.4 | Tray Tower Scrubbers | 600 - 23 |
| 605.4.1 | Sieve Tray Scrubbers | 600 - 26 |
| 605.4.2 | Catenary Grid Scrubbers | 600 - 26 |
| 605.5 | Packed Bed Scrubbers | 600 - 27 |
| 605.5.1 | Cross-flow and Counter-flow Arrangements | 600 - 28 |
| 605.5.2 | Fixed Packed Bed Scrubbers | 600 - 29 |
| 605.5.3 | Moving Bed Scrubbers | 600 - 31 |
| 605.5.4 | Flooded Bed Scrubbers | 600 - 32 |
| 605.6 | Wet Ionizing Scrubbers | 600 - 34 |
| 605.7 | Froth Scrubbers | 600 - 35 |
| 605.8 | Gas-Atomized Scrubbers | 600 - 35 |
| 605.8.1 | Venturi Scrubbers | 600 - 35 |
| 605.8.2 | Rod Deck Scrubbers | 600 - 41 |
| 605.8.3 | Collision Scrubbers | 600 - 42 |
| 605.8.4 | Orifice Scrubbers | 600 - 42 |
| 605.9 | Ejector Venturi Scrubbers | 600 - 43 |
| 605.10 | Gas Ejector Scrubbers | 600 - 44 |
| 605.11 | Condensation Growth Scrubbing Systems | 600 - 44 |
| 606 | CYCLONE SYSTEMS AND DESIGNS | 600 - 45 |
| 606.1 | Cyclone Collection Mechanisms | 600 - 47 |
| 606.2 | Large Diameter Cyclones | 600 - 49 |
| 606.2.1 | Solids Discharge Valves | 600 - 50 |
| 606.3 | Multi-Cyclones | 600 - 54 |
| 606.4 | Cyclonic Scrubbers | 600 - 57 |
| 606.5 | Cyclone Theory | 600 - 58 |
| 606.5.1 | Predicting Pressure Drop | 600 - 59 |
| 607 | MIST ELIMINATION | 600 - 60 |
| 607.1 | Types of Mist Eliminators | 600 - 60 |
| 607.1.1 | Cyclonic Vessels | 600 - 61 |
| 607.1.2 | Chevrans | 600 - 62 |
| 607.1.3 | Mesh Pad Mist Eliminators | 600 - 64 |
| 607.1.4 | Woven Pad Mist Eliminators | 600 - 65 |
| 608 | SCRUBBER PLUMES | 600 - 66 |
| 609 | COMPONENTS OF THE OVERALL SCRUBBING SYSTEM | 600 - 67 |
| 609.1 | Hoods and Fans | 600 - 71 |
| 609.2 | Pumps | 600 - 71 |
| 609.3 | Clarifier System | 600 - 72 |
| 609.4 | Cooling Towers | 600 - 72 |
| 609.5 | Instrumentation | 600 - 73 |
| 610 | CHOOSING NEW SCRUBBERS FOR INDUSTRIAL PROCESSES | 600 - 75 |
| 610.1 | Empirical Evaluation | 600 - 75 |
| 610.2 | Pilot Scale Tests | 600 - 76 |
| 610.3 | Theoretical Penetration Models | 600 - 77 |
| 611 | FLUE GAS DESULFURIZATION | 600 - 77 |

| | | |
|---------|---|-----------|
| 611.1 | Wet Slurry Throwaway Scrubbing..... | 600 - 79 |
| 611.2 | Wet Solution Throwaway Scrubbing | 600 - 80 |
| 611.3 | Sulfur Producing Scrubbing Systems | 600 - 80 |
| 611.4 | Dry Scrubbing | 600 - 81 |
| 612 | RULE DISCUSSION | 600 - 82 |
| 612.1 | NSPS | 600 - 82 |
| 612.2 | District Regulations and Permits | 600 - 83 |
| 612.2.1 | Visible Emissions | 600 - 83 |
| 612.2.2 | Particulate Matter Emissions Limits | 600 - 85 |
| 612.2.3 | Gaseous Emissions | 600 - 89 |
| 612.2.4 | Permits | 600 - 92 |
| 613 | INSPECTION INTRODUCTION | 600 - 94 |
| 613.1 | Sequence of Inspection | 600 - 95 |
| 613.1.1 | Co-Current Approach | 600 - 95 |
| 613.1.2 | Counter-Flow Approach | 600 - 96 |
| 613.1.3 | Other Approaches | 600 - 96 |
| 613.2 | Levels of Inspection | 600 - 96 |
| 614 | PRE-INSPECTION PROCEDURES | 600 - 97 |
| 614.1 | File Review | 600 - 97 |
| 614.2 | Regulation Review | 600 - 98 |
| 614.3 | Equipment Check | 600 - 98 |
| 614.4 | Pre-Entry and Entry | 600 - 98 |
| 614.5 | Pre-Inspection Meeting..... | 600 - 98 |
| 615 | SCRUBBING SYSTEM INSPECTION | 600 - 99 |
| 615.1 | Scrubber Visible Emissions (All Levels) | 600 - 99 |
| 615.2 | Droplet Reentrainment | 600 - 100 |
| 615.3 | Scrubber System General Physical Conditions (Levels 2,3,4) | 600 - 101 |
| 615.4 | Scrubber Static Pressure Drop (Levels 2,3,4) | 600 - 101 |
| 615.4.1 | Level 3 and 4 Inspections | 600 - 101 |
| 615.5 | Gas Outlet Temperature | 600 - 103 |
| 615.6 | Gas Flow Rate | 600 - 103 |
| 615.7 | Liquor Inlet Pressure (Levels 2,3,4) | 600 - 104 |
| 615.8 | Liquor Turbidity and Solids Settling Rate (Levels 2,3,4) | 600 - 104 |
| 615.9 | Liquor Ph (Levels 2,3,4) | 600 - 105 |
| 615.10 | Scrubber Liquor Recirculation Rate (Levels 2,3,4) | 600 - 105 |
| 615.11 | Demister Inspection (Levels 2,3,4) | 600 - 106 |
| 615.12 | Inspecting the Inside of Particular Scrubber Designs (Levels 2,3,4) | 600 - 109 |
| 615.13 | Process Inspection | 600 - 109 |
| 616 | CYCLONE INSPECTION | 600 - 110 |
| 616.1 | Visible Emissions | 600 - 110 |
| 616.2 | Cyclone Physical Conditions | 600 - 111 |
| 616.3 | Solids Discharge Valve | 600 - 111 |
| 616.4 | Static Pressure Drop | 600 - 111 |
| 616.4.1 | Level 3 and 4 Inspections | 600 - 112 |
| 616.5 | Air Infiltration | 600 - 114 |
| 616.5.1 | Level 3 and 4 Inspections | 600 - 114 |
| 616.6 | Process Inspection | 600 - 114 |

| | |
|--|------------------|
| 617 CYCLONE PROBLEMS AND FAILURES | 600 - 115 |
| 617.1 Plugging and Erosion | 600 - 115 |
| 617.1.1 Plugged Discharge | 600 - 115 |
| 617.2 Air Infiltration | 600 - 116 |
| 617.3 Cross-Hopper Gas Movement | 600 - 117 |
| 617.4 Particle Bounce | 600 - 117 |
| 617.5 Gas Flow Rate | 600 - 119 |
| 618 POST-INSPECTION PROCEDURES | 600 - 119 |

APPENDICES

| | |
|---|--------------|
| A. References | A - 1 |
| B. California Health and Safety Code | B - 1 |

GLOSSARY

INDEX

LIST OF FIGURES

| | |
|---|----------|
| 106.1 Hood with Velocities | 100 - 8 |
| 106.2 Hood Velocities with Baffles | 100 - 9 |
| 106.3 Hood Capture Push-Pull Method | 100 - 10 |
| 106.4 Basic Elements of Air Pollution Control System..... | 100 - 10 |
| 106.5 Fan Blade Types | 100 - 13 |
| 106.6 Fan Characteristic Curves..... | 100 - 15 |
| 106.7 Fan System Curve and Characteristic Curve | 100 - 15 |
| 201.1 Charges on Polar and Non-Polar Molecules | 200 - 2 |
| 201.2 Adsorbate and Adsorbent..... | 200 - 3 |
| 204.1 Representation of Carbon Bed Structure | 200 - 7 |
| 205.1 Adsorption Mechanism..... | 200 - 9 |
| 205.2 Pore Space Representation | 200 - 11 |
| 205.3 Capacity vs. Distance Through Bed | 200 - 12 |
| 205.4 Pore Space at Different Distances Through Bed | 200 - 13 |
| 205.5 Concentration vs. Distance Through Bed | 200 - 14 |
| 205.6 Outlet Concentration Curve..... | 200 - 16 |
| 207.1 Pounds of Steam from Regeneration vs. Working Capacity | 200 - 20 |
| 207.2 VOC Concentration vs. Distance Through Bed After Regeneration | 200 - 21 |
| 207.3 Adsorption/Desorption Cycle Times | 200 - 23 |
| 208.1 Adsorption Capacity vs. Temperature at Constant Pressure | 200 - 26 |
| 209.1 Rotary Carbon Adsorption System..... | 200 - 33 |
| 210.1 Bulk Plant Adsorber and Absorber..... | 200 - 35 |
| 211.1 Main Components of Carbon Adsorber Using Steam Regeneration | 200 - 37 |
| 212.1 Calculating Adsorption Efficiency | 200 - 39 |
| 303.1 Packed Column | 300 - 6 |
| 303.2 Series Countercurrent-Cocurrent Absorption System | 300 - 8 |
| 303.3 Common Absorber and Scrubber Packings..... | 300 - 10 |
| 303.4 Bubble Cap Plate Column | 300 - 14 |
| 402.1 Contact Condensers | 400 - 4 |
| 402.2 Shell and Tube Exchanger (Simplified)..... | 400 - 5 |
| 402.3 Refrigeration Vapor Recovery System | 400 - 12 |
| 502.1 Thermal Incinerator with Horizontal Burner..... | 500 - 7 |
| 502.2 Single Flame Incinerator without Auxiliary Air | 500 - 8 |
| 502.3 Vertical Thermal Incinerator with Air Damper..... | 500 - 9 |
| 502.4 Effects of Residence Time and Temperature on Destruction Efficiency | 500 - 10 |
| 502.5 Multijet Afterburner | 500 - 11 |
| 502.6 Catalytic Incinerator | 500 - 12 |
| 601.1 Suspended Particulate Size Matter (PM10)..... | 600 - 3 |
| 602.1 Relative Size of 100, 10 and 1 Micron Particle..... | 600 - 6 |
| 602.2 Particle Shapes | 600 - 7 |
| 602.3 Martin's Diameter and Feret's Diameter | 600 - 7 |
| 603.1 Main Particle Collection Mechanisms..... | 600 - 12 |
| 605.1 Spray Tower | 600 - 20 |

| | | |
|--------|---|-----------|
| 605.2 | Wet Dynamic/Mechanical Scrubber | 600 - 22 |
| 605.3 | Vertical Spray Rotor Scrubber | 600 - 23 |
| 605.4 | Tray Tower Scrubber | 600 - 24 |
| 605.5 | Cross-Flow Scrubber | 600 - 28 |
| 605.6 | Packed Column | 600 - 30 |
| 605.7 | Moving Bed Scrubber | 600 - 31 |
| 605.8 | Flooded Bed Scrubber | 600 - 33 |
| 605.9 | Wet Ionizing Scrubber | 600 - 34 |
| 605.10 | Venturi | 600 - 37 |
| 605.11 | Impaction of Particles and Target Droplets in Venturi | 600 - 37 |
| 605.12 | Venturi Scrubber Liquid Feeds | 600 - 39 |
| 605.13 | Rod Deck Scrubber | 600 - 41 |
| 605.14 | Orifice Scrubber | 600 - 43 |
| 605.15 | Condensation Growth Scrubber System | 600 - 46 |
| 606.1 | Large Diameter Cyclone | 600 - 47 |
| 606.2 | Movement of Particles Across Gas Stream Lines | 600 - 48 |
| 606.3 | Cyclone Inlets | 600 - 51 |
| 606.4 | Bottom Inlet Cyclone | 600 - 51 |
| 606.5 | Series and Parallel Cyclone Arrangements | 600 - 52 |
| 606.6 | Discharge Valves | 600 - 53 |
| 606.7 | Multi-Cyclone | 600 - 55 |
| 606.8 | Small Diameter Cyclone from Multi-Cyclone | 600 - 56 |
| 607.1 | Cyclonic Demister with Venturi Scrubber | 600 - 61 |
| 607.2 | Chevron Mist Eliminator | 600 - 63 |
| 607.3 | Mist Eliminator with Phase Separation Chambers | 600 - 64 |
| 607.4 | Mesh Pad Mist Eliminator | 600 - 65 |
| 608.1 | Psychometric Chart | 600 - 68 |
| 609.1 | Simplified Scrubber System | 600 - 69 |
| 617.1 | Cross-Hopper Gas Movement in Multi-Cyclone | 600 - 118 |

LIST OF TABLES

| | |
|---|-----------|
| 107.1 Variances | 100 - 26 |
| 216.1 Carbon Adsorption Inspection Form A | 200 - 52 |
| 216.2 Carbon Adsorption Inspection Form B | 200 - 53 |
| 405.1 Condenser Standards for Perchloroethylene Dry Cleaning Systems | 400 - 18 |
| 405.2 Condenser Limitations for Pharmaceuticals and Cosmetics Manufacturing | 400 - 19 |
| 405.3 Condenser Limits for Solvent Cleaning Operations (BAAQMD) | 400 - 20 |
| 405.4 Condenser Limits for Solvent Degreasers (SCAQMD) | 400 - 21 |
| 408.1 Condenser Inspection for Inspection Form | 400 - 31 |
| 502.1 Concentration for 25% of LEL for Common Compounds | 500 - 6 |
| 502.2 Temperatures Required for 90% Oxidation of Common Compounds | 500 - 14 |
| 502.3 Catalytic Incinerator Temperatures and Applications | 500 - 15 |
| 502.4 Catalyst Inhibitors | 500 - 18 |
| 507.1 Incinerator Inspection Form | 500 - 33 |
| 603.1 Particle Terminal Settling Velocities | 600 - 15 |
| 607.1 Velocities for Common Mist Eliminator Designs | 600 - 62 |
| 612.1 Relationship Between Light Transmission, Ringelmann and Opacity | 600 - 84 |
| 612.2 Particulate Matter - Concentration | 600 - 86 |
| 612.3 (SCAQMD Rule 404) Max. Concentration of PM Allowed in Discharged Gas | 600 - 87 |
| 612.4 (SCAQMD Rule 405) Max. Discharge Rate of Particulate Matter | 600 - 88 |
| 612.5 District Regulations for Sulfur Compounds | 600 - 90 |
| 612.6 District Regulations for Nitrogen Oxides | 600 - 91 |
| 615.1 Possible Causes of Low or High Pressure Drops in Some Scrubbers | 600 - 102 |
| 615.2 Scrubber Inspection Form A | 600 - 107 |
| 615.3 Scrubber Inspection Form B | 600 - 108 |
| 616.1 Cyclone Inspection Form | 600 - 113 |

100 INTRODUCTION

VOC Control
Devices/
Scrubbers

101 AIR RESOURCES BOARD

The California Air Resources Board (CARB or ARB) was created by the California Legislature to control air pollutant emissions and to improve air quality throughout the State. Under direction of the California Environmental Protection Agency (Cal/EPA), the ARB works closely with the United States Environmental Protection Agency (EPA) and local air pollution control districts in improving air quality in California.

The CARB:

- Conducts inspections to ensure compliance with air pollution regulations;
- Develops rules and regulations to assist local air pollution control districts in their efforts to maintain air quality standards;
- Establishes air quality standards which identify acceptable concentrations of specific pollutants which are intended to protect the health of vulnerable members of the general population and to prevent property and crop damage;
- Monitors air quality throughout the State; and
- Evaluates the effectiveness of pollutant control strategies both for automobiles and industrial sources.

ARB
Responsibilities

102 COMPLIANCE ASSISTANCE PROGRAM

The Compliance Assistance Program (CAP), created in 1988 by the ARB, assists local air pollution control districts in conducting more comprehensive, consistent, and accurate facility compliance inspections. The CAP program also provides industry with information and tools, in the form of self-help publications, which clarify compliance requirements and help explain how to stay in compliance with air pollution rules and regulations. The CAP also assists industries in establishing their own compliance inspection programs. By

100 INTRODUCTION

conducting routine compliance inspections, industrial emissions sources can stay in compliance on a daily basis and can thereby avoid costly air pollution violations.

Through the development and distribution of rule-specific publications, the CAP creates an effective flow of information in a variety of useful formats. Based on the idea that sources will comply if they can understand what is required of them, CAP publications identify regulation requirements and present them in more readily readable formats.

Publication formats include:

Handbooks. Easy to read, colorfully illustrated handbooks are developed for the industrial labor force and the interested public. Most can be read in ten minutes or less and most contain helpful self-inspection checklists.

Pamphlets. Quick reference pamphlets are filled with detailed flow charts, checklists and informative diagrams. These are designed for facility managers, plant personnel and industry's environmental managers.

Technical Manuals. Detailed technical inspection manuals are developed for local air pollution control district inspectors and industry's environmental managers. These contain rule information, process descriptions and step-by-step compliance inspection procedures.

In 1988 California enacted legislation known as the California Clean Air Act. This act requires the air pollution control districts to attain the State and federal ambient air quality standards at the earliest practicable date, and requires each air pollution control district to prepare a plan showing how it will achieve this.

Enforcement audits of certain industrial source types (such as solvent degreasers, gasoline vapor recovery systems, and coating of metal parts) show that noncompliance rates can be as high as 50 percent. Noncompliance results in excessive emissions.

100 INTRODUCTION

VOC Control
Devices/
Scrubbers

Traditionally, ARB has sought to reduce noncompliance rates by providing an adequate deterrent through enforcement action against violators. In addition, ARB now seeks to reduce noncompliance rates and the associated excess emissions by ensuring that source operator knowledge includes:

- A basic understanding of the rules to which the source or product is subject; and
- A basic understanding of how compliance is to be determined.

If California's nonattainment areas are to have any chance of achieving the ambient air quality standards, the excess emissions resulting from noncompliance must be reduced by air pollution control inspectors and industry personnel. Air pollution control inspectors can identify problems for the source operator and propose corrective action, but their periodic visits cannot ensure continuous compliance. Compliance is the job of educated source operators. The goal of the Compliance Assistance Program is thus twofold:

- To help air pollution control districts develop and maintain inspector knowledge; and
- To encourage industry to do self-inspections for continuous compliance.

CAP Goals

102.1 TARGET AUDIENCE

This manual was written primarily for district field operation staff, district permitting staff, and environmental managers, but it may also be useful to other government agencies and industry personnel. It can be used as a reference manual or user's guide and it is designed for easy referencing, reading, and updating. It also contains graphics and illustrations to enhance understanding.

100 INTRODUCTION

103 MANUAL SCOPE AND ORGANIZATION

This manual deals with the following control devices: adsorbers, absorbers, condensers, oxidizers, scrubbers and cyclones. Separate, tabbed sections have been made for each of these devices except for the section on scrubbers and cyclones. Cyclones are discussed within the scrubber section. Within each section a process description, rule discussion and inspection discussion are included. The rule discussion and inspection section for absorbers is included in the scrubber section. The process descriptions describe what these control devices are, how they work, and the control or collection mechanisms they use to prevent air pollution. Where applicable, health effects and characteristics of pollutants are discussed. The rule discussions describe how equipment using these control devices is regulated by different government agencies. Following the rule discussion in each section is the inspection section. First, pre-inspection procedures are discussed, then the manual goes through the inspection procedures of the control device. After the scrubber section are the appendices, glossary, and index. These three sections apply to the whole manual. The glossary contains important terms from the manual; the index at the end of the manual provides easy access to information.

104 MAINTENANCE OF MANUAL

The Compliance Assistance Program welcomes your comments concerning this manual. Your comments and corrections, changes in legal requirements, and new information on equipment and processes will be collected and periodically distributed in an upgrade packet. Only the manual users who return the tracking card located in the very front of the manual will receive an upgrade packet, so be sure to fill out your card and send it in as soon as you receive the manual.

105 VOC HEALTH CONCERNS

Volatile organic compounds (VOCs) are basically carbon-containing compounds that evaporate at a high rate at relatively low temperatures. Many VOCs are also hydrocarbons or derived from hydrocarbons. Hydrocarbons are compounds made of carbon and hydrogen atoms.

100 INTRODUCTION

VOC Control Devices/ Scrubbers

Control devices are used to control the emissions of volatile organic compounds to the atmosphere from industrial processes and other human activities. Emissions of VOCs to the atmosphere are undesirable because hydrocarbons, nitrogen oxides (NO_x), and the energy of sunlight can create ozone (O₃).

105.1 OZONE

Ozone, a major component of smog, is California's worst pollutant problem. Ozone is called a photochemical pollutant since it is created by chemical reactions from the energy of the sun. Ozone is a very reactive chemical. When it forms in high concentrations in the lower atmosphere it damages plants, the lungs of people and the surfaces of cars and buildings.

Ozone attacks the leaves of plants and causes them to yellow, develop dead areas, and die. Ozone makes crops more susceptible to disease and insect attack and reduces their yield. Smog is estimated to cost California between 150 million to 1 billion dollars a year in crop damage.

Research sponsored by the Air Resources Board has shown that exposure to ozone damages the alveoli, the air sacs in the lungs where the exchange of oxygen and carbon dioxide between the air and blood takes place. This injury results in lung inflammation and changes in breathing. Repeated injury is thought to lead to permanent lung damage. Exposure to ozone can also cause burning sensations in the chest, throat, and eyes.

105.2 VOC

Not only do emissions of volatile organic compounds in the atmosphere cause the formation of smog, many VOCs are directly toxic or hazardous to a person's health. Exposure to VOCs can have specific acute (short term) and chronic (long term) effects. Acute health effects of VOCs include: irritation and burning of the eyes, skin, nose and throat; dizziness, headache, and nausea; and even respiratory arrest. Chronic effects caused by VOCs entering the blood stream through the lungs or skin include: permanent vision damage, liver disease, kidney disease, contact dermatitis, and nervous system disorders.

100 INTRODUCTION

Workers at a facility may have a permissible exposure limit (PEL) to VOCs, which is the amount of a compound that workers can be safely exposed to in an eight hour day.

105.2.1 Sources of VOCs and Hydrocarbons

Organic Gases

Organic gases can basically be emitted to the atmosphere from the production, processing, storage, transport, use and disposal of organic materials. There are numerous sources of volatile compounds but some of the major sources will be discussed in this section.

Petroleum Production Processing and Distribution

Petroleum production, processing, and distribution - Hydrocarbons can leak from oilfield equipment and refining equipment including: storage tanks, blow down systems, catalyst regenerators, processing vessels, flares, pumps, compressors, and waste effluent equipment. Hydrocarbon vapors are emitted by gasoline distribution and marketing facilities from loading racks, storage tanks, and automobile tank filling.

Solvents

Organic solvents - Many solvents are derived from petroleum. They are used in petrochemical operations, pharmaceutical operations, dry cleaning operations, solvent degreasing operations, numerous coating operations, aerospace operations, graphic arts printing operations, polyester resin manufacturing, rubber and plastic production, and others.

Combustion

Waste disposal/combustion - Inefficient incinerators can release unoxidized organic material into the air.

Other sources - Foundries and metallurgical coke plants, fermentation processes, food processing, and organic fertilizer production.

106 AIR POLLUTION CAPTURE SYSTEMS

106.1 HOODS

Pollutant laden air from a process must be enclosed or captured and sent to a control device by the use of hoods. Hoods are simply widened portions of a duct, where the dirty gas is initially drawn in with a fan by negative pressure. They can be round or rectangular ducts or plenums and they can simply be part of the control device.

Pollutants that are not captured by the hood may disperse into the plant and eventually into the atmosphere. Hood capture efficiency can have a major effect on emissions. If, for example, emissions are 100 lbm/hr (pound-mass per hour) and the hood and scrubber are 95% efficient the following emissions will be released:

Hood: $(100 \text{ lbm/hr})(.95) = 95 \text{ lbm/hr}$ collected
 $100 - 95 \text{ lbm/hr} = 5 \text{ lbm/hr}$ fugitive emissions from hood

Scrubber: $(95 \text{ lbm/hr})(.95) = 90.25 \text{ lbm/hr}$ collected
 $95 - 90.25 \text{ lbm/hr} = 4.75 \text{ lbm/hr}$ emissions from stack

Amazingly, the hood can have a greater effect on emissions than the control device.

In order to get emissions into a hood the emission source must be as close as possible to the hood. Less than a hood diameter away from the hood entrance, the gas velocity drops to 10% of the gas velocity at the entrance.¹ Figure 106.1 illustrates how rapidly the gas velocity decreases moving away from the hood entrance. The difficulty in getting emissions to flow into a hood with negative pressure can be compared to blowing out a candle versus "sucking out" a candle.

In applications where the gas stream is hot, the hood is placed above the gas stream to maximize capture effectiveness. A relatively hot gas stream will tend to rise up into the hood because it has a lower density than the surrounding cooler gases.

100 INTRODUCTION

Side Baffles

The addition of side baffles to a hood are a means of improving capture efficiency (Fig. 106.2)¹. Side baffles help prevent clean air from around the sides of the hood from being drawn into the system. Side baffles also help prevent the motion of air into the hood from being disturbed by cross drafts. The side baffles can be made of sheet metal, plastic, or even sheets of fabric.

Some equipment may not need a hood because the existing process equipment serves as a hood.¹ Coal fired boilers, for example, are maintained at a negative static pressure between -0.05 and -0.25 inches of water. In order to maintain the negative pressure in the boiler a flow of flue gas from the low pressure in the boiler toward the control device is maintained. In such a system, the boiler serves as the hood.

Another method used to gather emissions with a hood is to use the "push-pull" hood (Fig. 106.3). A high velocity of clean ventilation air is blown in the direction of the hood across the area containing pollutants. The gas stream does not disperse very rapidly and captures the pollutant laden gas as it flows toward the hood.

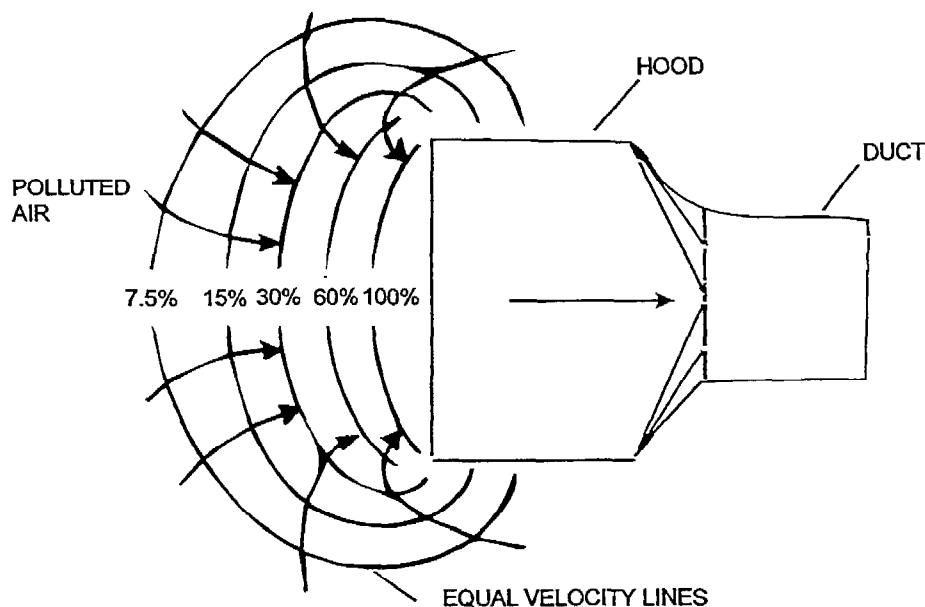
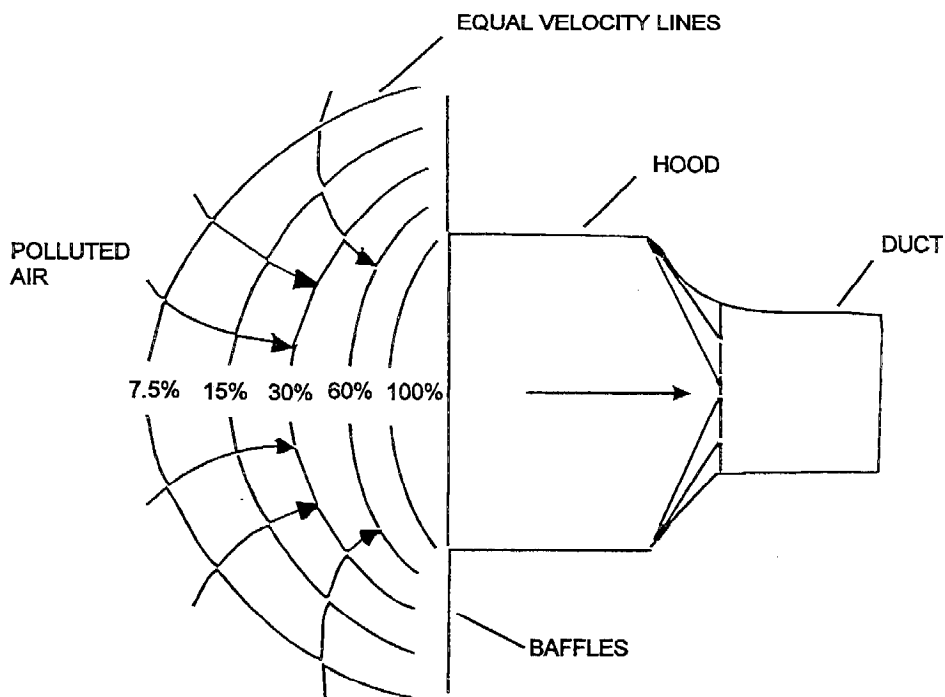


Figure 106.1 Hood with Velocities



**Figure 106.2 Hood Velocities
with Baffles**

Figure 106.4 illustrates how the capture system fits in the main elements of an air pollution control system. Emissions from a process are captured by hoods, but some fugitive emissions may escape into the atmosphere. Pollutants are sent to a control device (adsorber, scrubber, baghouse, etc.) and removed from the waste stream; wastes from pollutant removal are continually or periodically removed from the control device. Exhaust then exits the stack of the process and any remaining pollutants in the exhaust will be emissions.

106.2 FANS/BLOWERS

Fans (also called blowers by some regulatory and industrial personnel) can be an important part of an air pollution control system. They control the gas flow rate from where pollutants are generated, through the control device and out of the stack.

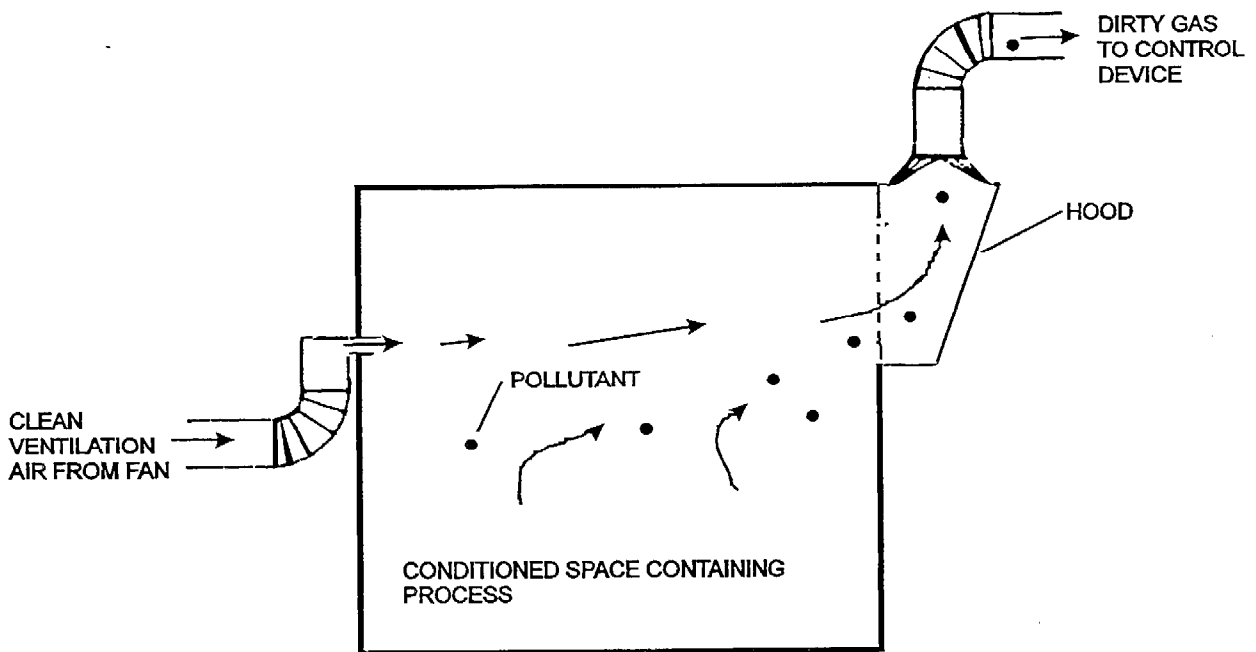


Figure 106.3 Hood Capture Push-Pull Method

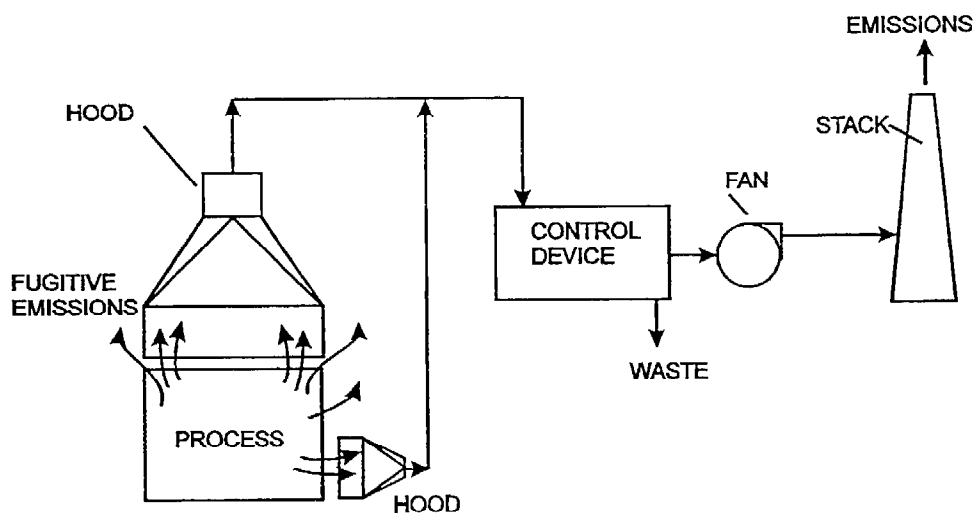


Figure 106.4 Basic Elements of Air Pollution Control System

100 INTRODUCTION

VOC Control
Devices/
Scrubbers

The air pressure exerted in ducts by fans is usually measured with water manometers in inches of water column from graduations on the gauge. These pressure readings give the pressure inside the ductwork relative to atmospheric pressure. This pressure is called the gage pressure. Standard atmospheric pressure is 14.7 pounds per square inch (psi), which is also equivalent to 29.92 inches of mercury or 407.1 inches of water column. Furthermore, 14.7 psi absolute (psia) is 0.0 psi gage (psig). For example, when a tire air pressure gauge is not being used it will read 0.0 psi. The pressures the tire gauge measures are pressures over atmospheric pressure. Negative pressures indicated by a gauge or manometer are pressures less than 14.7 psi.

Gage Pressure

Fans impart energy to a gas stream by increasing static pressure and providing kinetic energy to a gas stream. Static pressure is the part or component of pressure exerted by stationary gases. The energy from the motion of a gas stream also contributes to pressure, and this pressure is called the velocity pressure. Fan energy is needed to overcome the losses in air velocity within ducts of the system. Fans are basically either axial or centrifugal.

106.2.1 Axial Fans

Axial fans are basically propeller fans. Standard household fans, for example, are axial fans. Their axis of rotation is parallel to the direction of the air flow. Axial fans can move large volumes of relatively clean air but they cannot generate a lot of static pressure.

Axial fans are usually used when over 500,000 cfm (cubic feet per minute) are required with a static pressure under 12 inches of water.² Since axial fans don't create a lot of static pressure, they are not used as much as centrifugal fans in industrial applications.

The two major types of axial fans are tubeaxial fans (also called duct fans) and vaneaxial fans. Tubeaxial fans have four to eight blades and the diameter of the hub is less than half of the diameter of the fan measured tip-to-tip. The blades of a tubeaxial fan generally cover the whole area of the duct where the fan is being used, with only a small clearance between the fan and the duct's

Two Types of Axial Fans

100 INTRODUCTION

walls. Tubeaxial fans are usually used to create three inches of static pressure or less.² Vaneaxial fans are different from tubeaxial fans in that they usually have vanes in the duct to straighten the air flow. The propellers of axial fans create a rotating motion in the gas stream and vanes help straighten the rotation. Furthermore, vaneaxial fans have a hub diameter greater than half the diameter of the fan blades and they can develop up to 12 inches of static pressure. They also have up to 24 blades which may have an airfoil shape.²

106.2.2 Centrifugal Fans

Unlike axial fans, centrifugal fans have an axis of rotation perpendicular to the air flow. They have an impeller (wheel containing the fan blades) that is somewhat similar to a rotating hamster cage. Centrifugal fans are generally good for air pollution control systems since they can develop high pressures and volume flow rates. They are generally used to produce pressures up to 60 inches of water and flow rates under 1,000,000 cfm.²

Fans are usually driven by electric motors. The main ways the fan energy is transferred to the fan is through belts, a direct drive or variable drive. In a fan using a belt drive, the motor's rotation is transferred to the shaft of the fan by multiple belts from sheaves on the motor shaft and the shaft of the fan. If the fan is driven by belts, the fan velocity will vary by the motor's velocity and the ratio between the diameters of the sheaves on the fan and the motor. If the belts slip, the fan velocity can be reduced several hundred rpm (revolutions per minute). A reduction in fan speed can lower the static pressure, flow rate, and air velocity and therefore reduce collection efficiency at the control device. Slipping belts usually make a loud squealing sound.

In a fan using a direct drive, the fan motor and fan blades are directly connected by a shaft. The fan and the motor will always have the same speed. If the fan and motor are connected by a gear train, the angular velocity of the fan and motor will always vary by the same ratio.

Variable speed fans can operate with a fan blade angular velocity independent of the motor angular velocity. This is done through the use of hydraulic or magnetic couplings which allow workers to automatically control the fan speed.

100 INTRODUCTION

VOC Control
Devices/
Scrubbers

Dampers are devices that can be used to control the flow rate from a fan without altering the operation of the fan. They are a series of vanes put across the inside of a duct that can be manipulated manually or automatically. Dampers can be situated upstream or downstream of a fan. Dampers upstream of a fan control how the gas stream enters the fan and can be adjusted to improve fan efficiency.

Dampers

106.2.3 Fan Blade Types

The main types of fan blade designs used for centrifugal fans include: backward curved, airfoil, forward curved and radial. These designs primarily differ according to the shape of the fan blade relative to the direction of rotation of the fan.

Backward curved fan blades have their blades curved away from the direction of rotation (Fig. 106.5)¹. These fans can operate over a large range without creating unstable air. They produce a relatively small amount of noise and the minimum amount of noise is created at the highest efficiencies. Backward curved fans have a high efficiency that is slightly lower than airfoil fans. Backward curved fans can handle gas streams with low particulate loads.

**Backward
Curved**

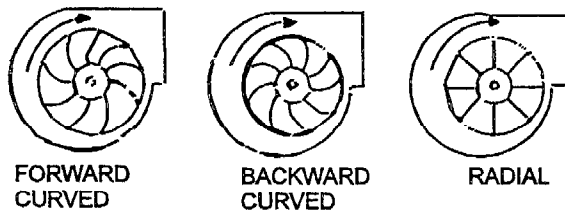


Figure 106.5 Fan Blade Types

Airfoil fans are the centrifugal fans with the highest efficiency. They have blades with an airfoil contour curved away from the direction of flow like backward curved fans. The operating characteristics of this fan are also very similar to backward curved fans. Air foil fans are usually used to handle clean air in heating, ventilating, and air conditioning applications. These fans cannot handle corrosive and erosive environments as well as backward curved fans.

Airfoil

100 INTRODUCTION

Forward Curved

Forward curved fan blades have their blades curved in the direction of fan rotation (Fig. 106.5). These fans create the least noise when being operated to produce maximum pressure. Maximum efficiency also occurs when the maximum pressure of the fan is being produced. As the flow rate from a forward curved fan rises, the power requirement rises rapidly. Forward curved fans are not good for handling dirty gas streams. They are very prone to the buildup of solids on the blades.

Radial

Radial fan blades are perpendicular to the tangents of the fan hub and do not have any curve (Fig. 106.5). Fans with this type of blade design have the lowest efficiency. Radial fans have a high mechanical strength and the impeller (the wheel containing the blades) is easy to repair. They tend to develop higher static pressures than the previously mentioned fans. Radial-type fan blades can handle the highest solids loads and are the least prone to solids buildup.

106.2.4 Fan System Principles

Characteristic Curve

Figure 106.6 illustrates a fan characteristic curve. A fan can theoretically operate anywhere on the curve. It can produce the highest static pressures at the lowest gas flow rates or it can produce the highest gas flow rates at the lowest static pressures. The shape of the curve depends on the type of fan blades, the angular velocity, and the shape of the fan housing. The shape of the fan characteristic curve can shift with changes in the fan speed (Fig. 106.6).

Due to leaks, dampers, temperature changes, vapor growth, and resistance in the duct system, static pressure is lost throughout the ducts and control devices handling the gas flow. The pressure loss varies approximately proportionally to the square of the velocity and also the flow rate. A plot of the pressure loss in a duct system is known as the system curve (Fig. 106.7). The intersection of the system curve and the fan characteristic curve denotes the operating point. This indicates the gas flow rate and static pressure rate that the fan is operating.

System Curve

If the resistance in a system increases, the system curve will shift to the left. For example, closing a damper in a duct system can increase system resistance. If this occurs the static pressure will increase, but the flow rate will decrease. A reduced flow rate can lower the capture efficiency at the hood. Emissions from

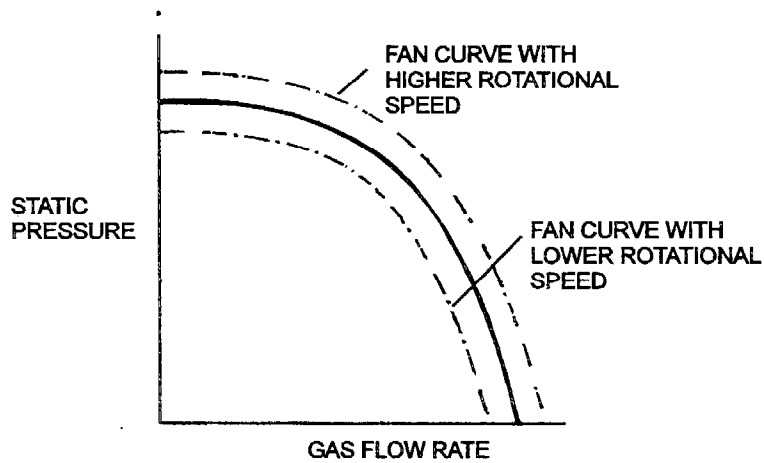


Figure 106.6 Fan Characteristic Curves

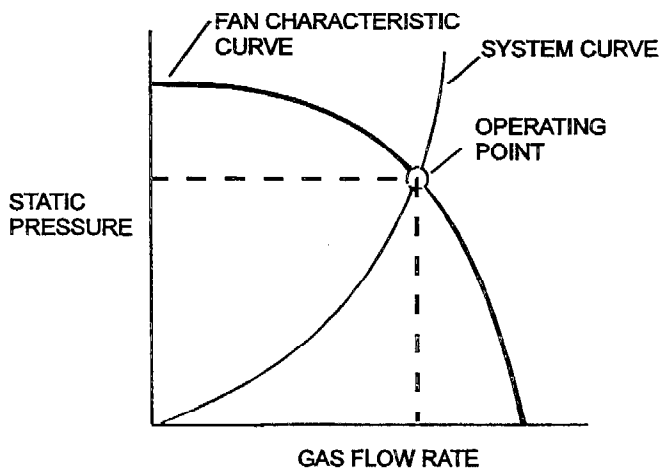


Figure 106.7 Fan System Curve
and Characteristic Curve

100 INTRODUCTION

the stack could still be within legal limits, but less emissions may be entering the emission control system from the hood. Excessive emissions could be emitted from the hood capture system.

If the system resistance drops it will cause the system curve to shift to the right. This would increase the flow rate in the system and decrease the static pressure. Lower system resistance would tend to improve the hood capture efficiency. On the other hand it could lower the capture efficiency in the control device.

Velocity Pressure

Besides the static pressure, fans also supply velocity pressure. It is the pressure due to the kinetic energy from the moving air. The velocity pressure can be calculated from the air velocity.

Velocity Pressure Equation

$$P_v = (\text{Velocity})^2 / 2g$$

Where:

V = Velocity (feet per second)

g = Acceleration due to gravity 32.2 ft/sec²

P_v = Velocity pressure (feet of air column)

Fan pressure is usually measured in inches of water column, not feet of air column. The units most often used for air velocity for fans is feet per minute (fpm). Therefore:²

$$P_v = [(V^2 / 2g)(1 \text{ min.} / 60 \text{ sec.})^2](\rho_{\text{air}} / \rho_{\text{water}})[12 \text{ in.} / 1 \text{ ft}]$$

$\rho_{\text{air}} = 0.075 \text{ lbm/ft}^3$ (standard air density, i.e. air density at 68°F)

$\rho_{\text{water}} = 62.4 \text{ lbm/ft}^3$ (standard water density, approximately 32°F - 60°F)

$$P_v = [V^2 / (60^2 (32.2))] (0.075 / 62.4) 12 \equiv (V / 4005)^2$$

V = Velocity, (feet per minute); P_v = Velocity pressure, (inches of water)

Note: Adjustments must be made to the above equation when there are large changes to temperature or pressure.

The sum of the static pressure and the velocity pressure are the total pressure.

$$P_t = P_s + P_v$$

P_s = Static pressure

P_t = Total pressure

100 INTRODUCTION

VOC Control Devices/ Scrubbers

Pressure can be converted from pounds per square inch gage (psig) to inches of water gage (w.g.) by dividing by the standard specific weight of water, which is numerically the same as the density of water ($\rho_{\text{water}} = 0.0361 \text{ lbm/in}^3$).²
inches w.g. = psig/0.0361 lbf/in³

The air horsepower, which is the theoretical fan horsepower at 100% efficiency, is:²

$$\text{AHP} = Q(\text{Pt})(0.0361 \text{ lbf/in}^3)[12 \text{ in/1 ft}]^2(1 \text{ hp/550 ft-lbf/sec})[1 \text{ min/60sec}]$$
$$\text{AHP} = Q\text{Pt}/6356$$

where:

AHP = Air horsepower (hp)

Q = Gas flow rate (ft³/min)

Pt = Total pressure (inches of water)

When inspections are conducted, it may be necessary to determine if there are changes in fan operation. Besides the use of manometers, the fan motor current provides a method to measure fan performance. In general, as the fan motor current increases, the gas flow rate increases and vice versa. The fan motor current can usually be found from an ammeter in a control room or near the fan. The following equation can be used to compute the brake horsepower (BHP) (the actual fan horsepower) for three phase fan motors:¹

$$\text{BHP} = (V)(I)(p_f)[3]^{0.5}$$

Where:

V = Voltage applied (volts)

I = Current (Amps)

p_f = Power factor (the phase relationship between current and voltage waveforms)

The fan efficiency is calculated by the following:

$$\eta_f = \text{AHP/BHP}$$

where:

BHP = Brake horsepower, the actual fan horsepower (hp)

η_f = Fan efficiency

106.2.5 Standard and Actual Conditions

Gas flow rates are often stated as either **standard** cubic feet per minute (scfm) or **actual** cubic feet per minute (acfm). Other units, such as standard cubic feet per second or actual cubic feet per second can be used. The flow rate of gases under standard conditions are at STP conditions (Standard Temperature and Pressure). STP conditions are at a pressure of one atmosphere (14.7 psi) and 32, 60, 68, or 70 degrees Fahrenheit. It is necessary to standardize conditions for gases because the temperature, pressure and volume of a gas are related (i.e. when the temperature of a gas is increased, its volume or pressure will increase). A gas flow that was measured under actual conditions (i.e. acfm) was measured at the existing temperature and pressure and has not been corrected to STP conditions. A form of the equation of state can be used to convert ideal gases from actual to standard conditions.²

$$PV = nR^*T$$

where:

P = Pressure (lbf/ft²)

V = Volume (ft³)

R* = Universal gas constant (1545.33 ft-lbf/pmole-°R)

n = number of moles

T = Temperature °R (Rankine)

$$R = R^*/M$$

$$n = m/M$$

where:

M = Molecular weight

m = mass (lbm)

R = Specific gas constant (ft-lbf/lbm-°R)

Therefore:

$$PV = (m/M)[M(R)]T = mRT$$

"m" and R are constant for an ideal gas undergoing a process from one state to another.

100 INTRODUCTION

VOC Control Devices/ Scrubbers

$$P_1 V_1 / T_1 = mR = P_2 V_2 / T_2$$

$$\text{therefore: } P_1 V_1 / T_1 = P_2 V_2 / T_2$$

"1" stands for the initial pressure, temperature, or volume; "2" stands for the final pressure, temperature, or volume. When converting from actual to standard conditions "1" would be the actual conditions and "2" would be the standard conditions. The equation can also be used in a similar manner to convert from standard to actual conditions. This relationship can also be used to correct volume flow rates of ideal gases. Volume flow rates would simply be substituted for the volume "V." Similar relationships can be used to convert from standard to actual conditions for density, pressure or motor current.

Examples:

$$P_{\text{actual}} / (\rho_{\text{actual}} T_{\text{actual}}) = P_{\text{STP}} / (\rho_{\text{STP}} T_{\text{STP}}) \quad \rho_{\text{actual}} = P_{\text{actual}} \rho_{\text{STP}} T_{\text{STP}} / (P_{\text{STP}} T_{\text{actual}})$$

where:

ρ = Density (mass/volume), i.e. lbm/ft³

The colder an air or gas stream in a system, the higher the current for a fan motor handling the air or gas stream will be. During cold operating periods, the flow rates are reduced by dampers to prevent the current from getting to high and damaging the fan motor. Once temperature and pressure are used to reach the standard and actual densities, the actual or standard motor current can be calculated.¹

$$I_{\text{actual}} \rho_{\text{STP}} = I_{\text{STP}} \rho_{\text{actual}} \quad I_{\text{STP}} = I_{\text{actual}} \rho_{\text{STP}} / \rho_{\text{actual}}$$

Where:

I = Current (amps)

| | |
|--------------------------------------|-------------------------|
| VOC Control Devices/ Scrubbers | 100 INTRODUCTION |
|--------------------------------------|-------------------------|

107 REGULATIONS

107.1 FEDERAL REGULATIONS

NSPS

The Federal Clean Air Act requires the U.S. Environmental Protection Agency (EPA) to establish new source performance standards (NSPS) for categories of sources which significantly contribute to air pollution. The NSPS apply both to new sources and to modifications to existing stationary sources of air pollution. The control devices discussed in this manual control emissions from stationary sources. The Clean Air Act directly prohibits operation of sources in violation of the NSPS.

40 CFR 60

The New Source Performance Standards are located in the Code of Federal Regulations, Title 40 Part 60 (40 CFR 60). The NSPS contain subparts ranging from A to VVV that give standards for a multitude of different processes. The requirements in the NSPS are specific to the type of operation. For example, Subpart TT is Standards of Performance for Metal Coil Surface Coatings. The regulation contains emission limits, requirements for thermal incinerators used to control VOCs and other prohibitions.

NESHAPS

At the federal level there are also standards regarding the emissions of toxic compounds called the National Emission Standards for Hazardous Air Pollutants (NESHAPS). These regulations have Subparts ranging from A to Y. The NESHAPS contain standards for compounds such as beryllium, asbestos and benzene.

EPA has the authority to delegate enforcement authority. EPA has delegated primary authority to several local districts in California and to the state in those districts not seeking delegation.

Federal Clean Air Act Amendments

The Federal Clean Air Act Amendments were last developed in 1990. The main parts of the amendments include:

Title 1 - Nonattainment Areas

Mandates for the EPA to make regulations to bring nonattainment areas into attainment for CO, O₃, and particulate matter pollution.

Title 2 - Mobile Sources

100 INTRODUCTION

VOC Control
Devices/
Scrubbers

Requirements for the EPA to issue regulations to reduce emissions from motor vehicles and automotive fuels.

Title 3 - Air Toxics

Requirements for EPA to issue standards to regulate 189 hazardous air pollutants.

Title 4 - Acid Rain

Mandates for EPA to issue new acid rain regulations, studies for NO_x emissions, clean coal, and industrial SO₂ emissions.

Title 5 - Permits

Requirements for EPA to issue new rules for Permit approvals and source exemptions.

Titles 6+7 - Stratospheric Ozone + Global Climate Change

Requirements for EPA to create new regulations and perform studies.

Title 8 - Miscellaneous

Provisions for electric cars, regulations for outer continental shelf operations and visibility studies.

Title 9 - Research

Studies addressing air pollution health effects, clean fuels, ecosystems and other items.

107.2 STATE REGULATIONS

State laws and statutes applicable to air pollution are in the California Health and Safety Code. Applicable Health and Safety Code requirements are in Appendix B.

Specific state regulations regarding air pollution are developed by the California Air Resources Board and are included in the California Code of Regulations (CCR). Title 13 contains regulations for mobile sources (cars, trucks etc.), Title 17 contains stationary source regulations, and Title 26 contains toxics

California Code
of Regulations

100 INTRODUCTION

California Clean Air Act Requirements

regulations. The Air Resources Board of the State of California primarily performs regulation and enforcement for mobile sources, consumer products, fuels, and abrasive blasting.

There is also a California Clean Air Act which went into effect in 1988. It basically requires the following:

1. The attainment of the state ambient air quality standards by the earliest practicable date.
2. All districts in violation of the state ozone, carbon monoxide, sulfur dioxide, or nitrogen dioxide standards must submit attainment plans every three years.
3. The California Air Resources Board must adopt the most effective emission controls possible for motor vehicles, fuels, consumer products, and mobile sources.
4. Districts subject to planning requirements must reduce emissions 5% a year until the relevant standard is achieved.
5. Rules and regulations within air basins must be uniform to the extent practicable, and the districts must coordinate individual planning efforts so that regional air quality issues are adequately addressed.

107.3 LOCAL (DISTRICT) REGULATIONS

Most of the regulation and enforcement is conducted by county air pollution control districts (APCDs) or multi-county air quality management districts (AQMDs). Districts regulate with their rules and by issuing Permits to Operate to companies owning or operating pollution generating equipment. Permits to Operate help simplify requirements in complex regulations for facility operators and owners so they can usually comply with most requirements by following their Permit. When a facility does not comply with a Permit or rule it may be given a Notice of Violation (NOV) and fined. Districts can also enforce the EPA rules and many have directly adopted the NSPS and NESHAPS regulations. In some cases district regulations are more stringent than the EPA's. District regulations cannot be less stringent than the EPA's.

100 INTRODUCTION

VOC Control
Devices/
Scrubbers

107.3.1 Equipment Breakdown Provisions

Most districts have an equipment breakdown (or excusable equipment malfunction) rule. The rule enables a source qualifying under stated conditions to avoid enforcement action when that source fails to comply with air pollution regulations as a result of a malfunction of any air pollution control equipment or related operating equipment. Malfunctions of in-stack monitoring equipment are also addressed in the rule.

Sources should keep a copy of the breakdown rule at the facility. They should also be familiar with their responsibilities in the event of an equipment malfunction.

The conditions that a malfunction must meet in order to qualify for district breakdown provisions vary between districts. Typically, the following conditions must be met in order to qualify for protection under the district's breakdown rule:

1. The breakdown must result from a failure that was unforeseeable;
2. It must not be the result of neglect or disregard of any air pollution control law, rule, or regulation;
3. It must not be intentional, or the result of negligence;
4. It must not be the result of improper maintenance;
5. It must not constitute a nuisance; and
6. It must not be an abnormally recurrent breakdown of the same equipment.

District rules also list a number of procedures which must be followed in reporting the breakdown in a timely manner to the district. If the breakdown is not reported to the district within the allowed time period, as stated in the rule, a separate violation occurs, for which enforcement action is appropriate.

When a breakdown is reported to the district it is recorded in the district's breakdown log. Sources must provide the district with the following information:

Conditions for
Breakdown
Qualification

100 INTRODUCTION

**Information
Provided by
Source to
District**

1. The source's name and location, and the source's contact name(s) and phone number;
2. The specific equipment affected by the breakdown;
3. The specific equipment that failed;
4. The date and time that the breakdown occurred;
5. The date and time that the breakdown is being reported to the district; and
6. The source's proposed action.

Upon receipt of a breakdown report, the district performs an investigation to determine whether the malfunction meets the prescribed breakdown conditions. This investigation includes an on-site inspection of the malfunctioning equipment. If the inspector does not find a breakdown condition at the source, they may take appropriate enforcement action. This may include fines, an abatement order, or an injunction against further operation.

If a source files a breakdown report which is false or without probable cause, or claims a malfunction to be a breakdown occurrence, this shall constitute a separate violation. The burden of proof shall be on the source to provide sufficient information that a breakdown did occur. If the source fails to do this, the district will undertake appropriate enforcement action.

A source with a breakdown must take immediate steps to correct the equipment malfunction as quickly as possible. If a source finds that a malfunction cannot be repaired within the district's allowable duration of a breakdown, the source may file for an emergency variance in order to avoid enforcement action.

**Details that
Must be
Submitted to
APCO**

District rules require sources to submit in writing the following details to the district air pollution control officer within a stated time period of the correction of the breakdown occurrence:

1. The duration of excessive emissions;
2. An estimate of the quantity of excess emissions;

100 INTRODUCTION

VOC Control Devices/ Scrubbers

3. A statement of the cause of the occurrence;
4. Corrective measures to be taken to prevent recurrences; and
5. Proof of the source's return to compliance, including the date and time that the breakdown was corrected.

Besides the information mentioned above, the district log will also include the following items, some of which will be completed as the case continues:

1. A confirmation that the breakdown is allowable under district rules;
2. The name of the district investigator;
3. The initial inspection file number;
4. The compliance confirmation inspection file number;
5. The date that the breakdown correction report was filed by the source; and
6. An indication if a variance was requested.

Information in District Log

107.4.1 Variances

A source may petition for a variance if either of the following is true:

1. Pollution control equipment has broken down and meets the criteria for breakdown condition under district rules; however, the source operator finds that it will take longer to repair the breakdown than provided for under the district breakdown rule.
2. A source finds itself to be out of compliance, is found to be out of compliance, or expects to soon be out of compliance, with any air pollution control district rule or regulation, or with Section 41701 of the California Health and Safety Code (H&SC). Table 107.1 illustrates the main types of variances. For complete information on variances, please consult the Health and Safety Code. The table provided here is only a quick summary.

Enforcement Relief for "Due Diligent" Sources

| Table 107.1 Variances | | | |
|--|--|--|---|
| Type of Variance | Effective Time Span | Noticing Requirements | Other Considerations |
| Emergency | 30 day maximum | None | 1 member may issue. Hearing Board determines eligibility for emergency |
| Short | 90 day maximum | 10 day minimum to APCO, air basin, EPA, ARB, and petitioner | 1 Hearing Board member may hear if district population < 750,000, unless a public member objects |
| Interim | 90 day maximum or until next Hearing Board meeting (whichever first) | Reasonable notice to APCO and petitioner | Same as short variance |
| Regular | 1 year maximum unless schedule of increments of progress included | 30 day minimum (15 if population < 750,000) to APCO, air basin district, ARB, EPA petitioner and any interested public | Public notice of hearing in at least one newspaper of general circulation in district |
| Modification of final compliance date (extension) | Determined by Hearing Board | Same as regular variance | Same as regular variance |
| Modification of schedule of increments of progress | Determined by Hearing Board | 10 days minimum to APCO, air basin, district, ARB, EPA, and petitioner | 1 Hearing Board member may hear if district population < 750,000, unless a public member objects |
| Interim authorization | 30 day maximum | Reasonable notice to APCO and petitioner | No more than one granted application if modification of schedule. 1 H. B. member may hear if pop. < 750,000, unless a public member objects |

100 INTRODUCTION

VOC Control
Devices/
Scrubbers

A source may petition for variance when they find themselves in violation of a district rule or regulation despite attempts made to cure the violation, or if a breakdown situation occurs. If a rule or regulation includes an Increments of Progress Schedule and a source cannot comply with the schedule in the rule or regulation, the source must apply for a modification of the schedule in accordance with H&SC 42357, except if the application requests a change in the final compliance date, which then makes them subject to the requirements of a variance as provided in H&SC 42352.

A variance provides a source temporary relief from enforcement action while steps are being taken by the source to bring itself back into compliance with the rule.

If it has been determined that a variance is necessary, a source then files a petition with a local air district. After the petition is properly noticed, a hearing is held. A variance can be granted provided specific findings of the H&SC can be made by the hearing board. The burden of proof and the presentation of findings to the board is on the petitioner (refer to H&SC 42352). The district staff most often assists the applicant with the petition and how to best present their case to the hearing board.

If a source applies for a short or regular variance and wishes to remain operating pending the decision and hearing on the regular or short application, it may apply for an interim variance. An interim variance is usually granted the same day it is applied for, and should expire on the date of the upcoming hearing. Emergency variances are granted for the breakdown condition described in #1 above. Emergency variances are also typically granted on the same day the petition is received.

It would be wise for a source to develop a compliance plan, to be presented to the hearing board as proof that they are on the road to compliance. The Air Resources Board recommends these plans for all variances; however, they are only required for a variance that exceeds a year. For help in developing such a plan, refer to H&SC 39051, which includes a typical schedule.

100 INTRODUCTION

Main H&SC Requirements

A source should be aware that the decision on whether to grant any variance rests with the district hearing board and not with the air pollution control officer or that person's staff. In general, the more information a source provides to the hearing board concerning its compliance problem, the better are its prospects of being granted a variance.

Rules for variance procedures vary somewhat from district to district. The district rules are based on H&SC statutes. Some of the applicable statutes are listed in Appendix B of this manual. District personnel as well as source operators should be familiar with these statutes and with the local district variance rule.

With regard to variances, State law (H&SC) requires that:

1. The district should not allow sources to operate in violation of district rules without a variance, even if the source is working towards finding a solution to the problem. Source operators should be aware that under H&SC Section 42400.2, if they continue to operate in violation of district rules, they are subject to a \$25,000 per day fine and up to 12 months in county jail.
2. All variance hearings should be noticed properly in accordance with H&SC Sections 40823 through 40827. Section 40826 requires a 30-day notice period for hearings for variances over a 90-day duration, except in small districts where there's a 15-day notice period for districts with a population under 750,000.
3. No variance shall be granted unless the hearing board makes all of the findings listed in H&SC, Section 42352. The burden of proof is on the petitioner to prove the findings at the hearing. District staff can give advice on how to best present the facts, but it is the petitioner's responsibility to present them.
4. No variance shall be granted if the granting of the variance is the result of source negligence, or if the variance will result in a nuisance.

100 INTRODUCTION

VOC Control Devices/ Scrubbers

The Air Resources Board recommends that the following procedures be observed in the various stages involved from the time a source petitions for a variance through the end of the variance period. Some of these recommendations may not be a part of all districts' variance programs at this time; or, they may be written but not implemented procedures.

ARB Recommendations for Variances

1. Parties petitioning for variance shall be required to fill out a petition form in writing.
2. The district will require sources to provide excess emissions figures on the petitions they submit. This information will be evaluated by the district staff. The emission figures are presented to the hearing board, so that the board formally recognizes, and the public may be aware of, the emissions impact of the variance. Excess emissions are an estimate of emissions. Any statements to abide by those estimates become an operating condition. Operating conditions shall be placed on the source, according to the H&SC.
3. An interim variance should be granted to only cover the time period needed to notice the petition for a regular variance and to render a decision on whether the variance is granted. This interim variance can subject the source to operating conditions during that interim period.
4. Variances should not be granted retroactively. The date that variance coverage begins cannot predate the date on which the petition was filed.
5. Each variance order will specify the equipment under variance and the district rule or regulation violated. By doing this, protection from enforcement action and the emissions resulting from granting the variance will be limited.
6. The district should schedule increments of progress for sources under variance, and should verify that the source is meeting these.
7. The district should require the source to quantify excess emissions that will occur during the period of variance, and to report these excess emissions according to a schedule.
8. At the end of the variance period, the district shall inspect the source to ensure that it is in compliance with all district air pollution regulations.

200 ADSORPTION

VOC Control
Devices/
Scrubbers

Adsorption is the condensation of a gaseous substance on a solid surface. Adsorption with carbon is a popular type of air pollution control of volatile organic compounds (VOCs) and odors.

The use of carbon adsorption for purification is not a new technology. The Egyptians were the first known to have used carbon as a purifying agent. In the thirteenth century, the ability of carbon to adsorb gases was discovered and carbonaceous materials began to be used to purify sugar solutions.

201 BASIC PRINCIPLES

When adsorption is used in control devices for air pollution, it is the removal of pollutants from a gas stream by attachment of the pollutants to a solid surface.

There are two types of adsorption: physical (van der Waals adsorption) and chemical adsorption.

201.1 PHYSICAL ADSORPTION

When physical adsorption occurs, a vapor condenses onto a solid without dissolving within the solid or chemically altering it.

Physical adsorption results from van der Waals forces occurring between molecules. Van der Waals forces, which were named after a Dutch scientist, are present in all matter.³ Van der Waals forces cause molecules and atoms to be attracted to each other because of electrons can move within atoms or molecules. Different parts of molecules can attain a charge and opposite charges will attract each other.

The effects of van der Waals forces can easily be seen and explained in polar molecules such as water (H_2O). Water molecules attract each other because one side of the molecule keeps a positive charge and the other side keeps a negative charge (Fig. 201.1). This is why the water molecule is also called a polar molecule. The oxygen atom is much bigger than the hydrogen atoms and it stays between the two hydrogen atoms at a 120° angle. The oxygen side tends to stay negative and the hydrogen side tends to stay positive because the

Van Der
Waals Forces

200 ADSORPTION

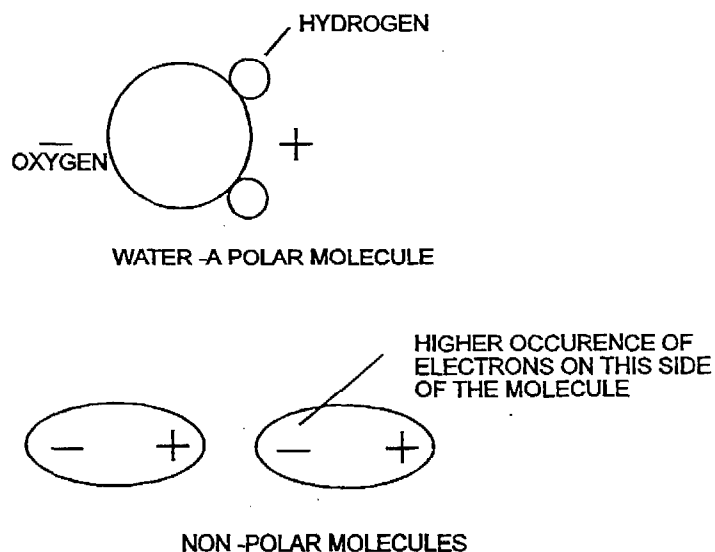


Figure 201.1
Charges on Polar and Non-polar Molecules

oxygen atom takes the electrons from the hydrogen atoms and the hydrogen atoms tend to give up their electrons. Water molecules align themselves so that their positive sides contact the negative sides of other molecules and vice-versa.

Droplets of water have an affinity for each other. When two droplets of water are connected they quickly join each other, becoming one larger drop of water. Water behaves in this manner because of van der Waals forces. Surface tension is another result of van der Waals forces. Light objects such as insects, leaves and even needles can float on water because of surface tension. Surface tension exists because of the intermolecular forces between water molecules.

Van der Waals forces also occur between the atoms of nonpolar molecules (many hydrocarbons are nonpolar molecules). They occur when one side of a nonpolar molecule becomes momentarily more negatively charged than the other by a change in the electron distribution in the atom for a very short period of time (Fig. 201.1). This causes other atoms nearby to become instantaneously polar, with more electrons occupying one side of the atom than the other, and the atoms attract each other. The attraction from van der Waals forces is

200 ADSORPTION

VOC Control
Devices/
Scrubbers

strongest when atoms are very close to each other. Atoms that have many electrons will have electrons that are not held to the atom as tightly, and the van der Waals forces will be stronger.

Van der Waals forces cause the condensation of water and other compounds from the gaseous state to the liquid state. When the intermolecular (van der Waals) forces between the molecules of a solid and a gas are greater than the intermolecular forces existing in a gas, condensation occurs on the solid.

Adsorption works more efficiently when it is conducted at high pressures and low temperatures near the dew point of the substance being adsorbed (adsorbate). The solid doing the adsorbing is the adsorbent (Fig. 201.2). Van der Waals adsorption is exothermic; it typically releases less than 40 Btu/lbmole.⁵

When several compounds are being adsorbed at once, the least volatile compounds will be adsorbed at a faster rate. When a solid gets close to the limit of the vapors it can adsorb, the more volatile compounds will tend to revaporize. The point where adsorption of the most volatile compounds starts to decrease is called the breakpoint.

Breakpoint

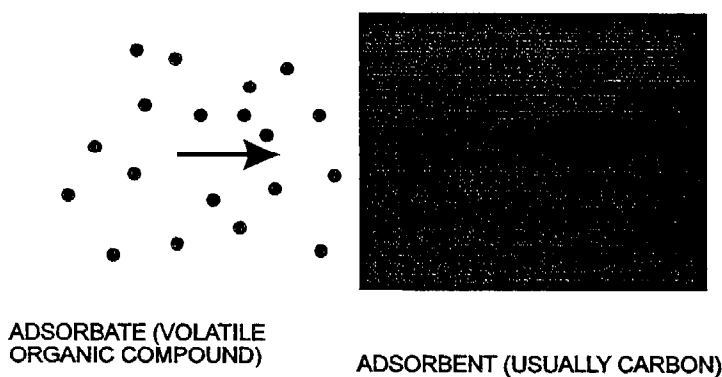


Figure 201.2
Adsorbate and Adsorbent

200 ADSORPTION

201.2 CHEMICAL ADSORPTION

Chemical adsorption, also called chemisorption or activated adsorption, occurs by chemical reactions between the adsorbent and the adsorbate. In chemical adsorption the substance being adsorbed is held more tightly to the solid than in physical adsorption. Chemical adsorption releases more energy than physical adsorption. Chemical adsorption gives off between 80 and 400 Btu/lbmole. When chemical adsorption is used, the solid and the gas are chemically altered, and the substance produced is generally nonrecoverable.

202 MATERIALS USED AS ADSORBENTS

Many solids have the ability to perform a small amount of adsorption, but only a few solids have the properties necessary to make it economical. In order for physical adsorption to be an efficient process, a large surface area in the solid (also called the adsorbent) is required. The layer of condensation that occurs from adsorption is extremely thin; it is only a few molecules thick. All adsorbents used for adsorption are made of porous materials to maximize the surface area of the solid surface available to condense and remove gases. The size of the pores in the material and the size of the molecules being adsorbed has an effect on the efficiency of adsorption. Large molecules will tend to block some pores in an adsorbent, preventing other molecules from entering them. Small molecules are more mobile and can usually diffuse around or in front of larger molecules into smaller pore spaces.

Substances such as charcoal (a form of carbon), hydrous oxides (silica gel, aluminum oxide, magnesium silicate), metals, natural materials (clays, bauxite, Fuller's earth) and molecular sieves can be used as adsorbents, but carbon is the adsorbent material usually used for air pollution control today. Carbon works well for the adsorption of hydrocarbons and non polar gases. Hydrous oxides are primarily for the adsorption of polar gases, metals work well operating as catalysts while adsorbing compounds, and natural materials have low adsorption capacities.

Some substances can have their adsorption characteristic improved by activation. Carbon is often activated to improve adsorption. Activating carbon involves heating it between 350-1000°C.⁵ The heat drives off hydrocarbon

200 ADSORPTION

VOC Control
Devices/
Scrubbers

molecules still left in the material and makes the carbon porous. When charcoal is activated, it improves the adsorption of carbon tetrachloride, for example, from 0.011 grams CCl_4 /gram Carbon to 1.48 grams CCl_4 /gram Carbon.⁵

203 ACTIVATED CARBON PRODUCTION

Activated carbon is produced by a process called pyrolysis.⁵ Pyrolysis is carbonization or destructive distillation. Organic substances are used to make activated carbon. Coal, petroleum residue, nut shells, coconut shells, and fruit pits are materials used to make activated carbon. Hardwoods, such as oak, birch, beech, and hard maple may also be used to make activated carbon. Carbonization is used to produce activated carbon from non-petroleum products, and destructive distillation of petroleum residue is used to produce coke, which can be made into activated carbon.

Pyrolysis

203.1 CARBONIZATION

During the carbonizing process organic material is slowly heated in several stages in the absence of air in large multiple-hearth furnaces or rotary kilns to form char, a black, charcoal-like substance.⁵ In the first stage the material is heated to 100°C, where water and the most volatile organic compounds are vaporized from the material. In the second stage the organic material is heated further to 170°C, forming some CO_2 and CO and organic acids. When the temperature reaches 270°C in the third stage, the process becomes exothermic and tars, methanol, and other distillates form. In the fourth and last stage, the organic material is heated to up to 400-600°C. When the temperature passes 350°C the pyrolysis ends, but the temperature is raised further to remove more of the less volatile tars.⁵ The high temperature treatments of the carbon make the carbon porous or "activated."

The activation process may be conducted for carbonous materials by heat treating them with steam without the presence of air. Zinc chloride, calcium chloride, magnesium chloride, and phosphoric acid have also been used as activating substances.

200 ADSORPTION

204 CARBON POROSITY

The pore structure of carbon is a very important factor in the ability of an adsorption system to control or recover VOCs. The tiny pores in activated carbon create an extremely large retention area for organic compounds. The carbon beds in adsorbers are made of a series of carbon pellets. Each pellet is made of carbon particles that have been sintered together (Fig. 204.1)⁶.

The external surface area of a carbon particle is a few square meters per gram, but the available surface area within the pores is, amazingly, hundreds of square meters per gram.⁶ The porous structure behaves like a sponge, retaining some VOCs even after the concentration in the carbon increases to a point where they begin to condense into a liquid. Some carbons can retain a mass of VOCs that is more than thirty percent over their own weight.

The pore space of carbon is characterized by three terms: micropores (<20 angstroms in diameter), mesopores (20-500 angstroms in diameter) and macropores (>500 angstroms in diameter).⁴ The type of material used to make activated carbon has an effect on the pore size. Coal based carbons tend to have more macropores and mesopores. Coconut shell carbon tends to have more micropores. Microporous carbons tend to be better for recovering highly volatile compounds such as methylene chloride.⁴ Macroporous carbon is better for the collection of heavier compounds. Heavy compounds, which are larger molecules and have a larger molecular weight, are harder to remove from microporous carbon during regeneration because of the smaller pore structure. Xylene and styrene emissions, for example, are handled better by carbon with a larger pore structure.

Although the type of material used to make activated carbon has a large effect on the porosity, the porosity of the carbon can be altered during activation. When a carbon is activated at relatively higher temperatures with a high ratio of carbon dioxide to steam, the pore size created will tend to be in the macroporosity range.⁴ On the other hand, if activation is performed in the presence of steam only, with lower temperatures over a relatively longer period of time, a more microporous structure will be developed.

**Micropores,
Mesopores and
Macropores**

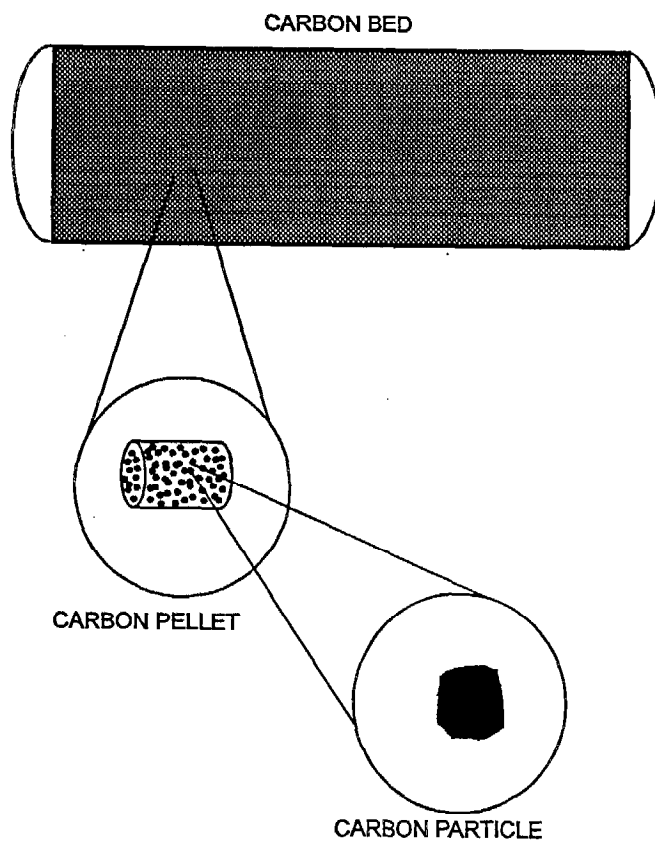


Figure 204.1
Representation of Carbon Bed Structure

200 ADSORPTION

205 THE CARBON ADSORPTION PROCESS

Carbon adsorption can be used to remove organic impurities from air or water. The removal of compounds from an air stream is gas phase carbon adsorption and the removal of compounds from water is liquid phase carbon adsorption. In air pollution the greatest concern is with gas phase carbon adsorption, but emissions of VOCs from wastewater is also a source of air pollution.

The carbon in an adsorber is used to transfer VOCs from a gas medium, which is a difficult medium to remove VOCs, to a solid medium where VOCs are more easily recovered. First the organic compounds are adsorbed on to the solid surface of the carbon and then the compounds are desorbed from the carbon and reused or disposed of.

The waste stream containing organic compounds is brought in contact with the carbon adsorber by a fan, blower, or similar air mover. When a carbon adsorber starts adsorbing compounds, the compounds first begin collecting in the carbon bed where the waste stream enters the adsorption vessel. Compounds diffuse from the surface of the carbon into the carbon pellets and then into the pores of carbon particles (Fig. 205.1). At first molecules stick for very short periods of time. As compounds diffuse from larger diameter pores to smaller ones, they begin to stick to the carbon for longer periods of time. Compounds continue to diffuse deeper into smaller pores until the diameter of the compound is at least about half the diameter of the pore that it occupies. At this point a compound does not have enough energy to escape from the pore because of the forces that hold it to the wall of the pore.⁶ The carbon will continue to adsorb compounds until the amount of compounds adsorbed on the carbon is in thermodynamic equilibrium with compounds in the gas phase.⁶ Thermodynamic equilibrium is dependent on the carbon type, the adsorbate partial pressure in the waste stream, and the temperature of the adsorbent and adsorbate.

The capacity of carbon adsorption by pore space is graphically illustrated in Figure 205.2. "A" represents the amount of adsorbate left over after regeneration. The adsorbate left in the carbon after regeneration is also called the **heel**. "B" represents the "working capacity" or the capacity available to adsorb pollutants. The total sum of "A" and "B" is the equilibrium capacity "C".⁶

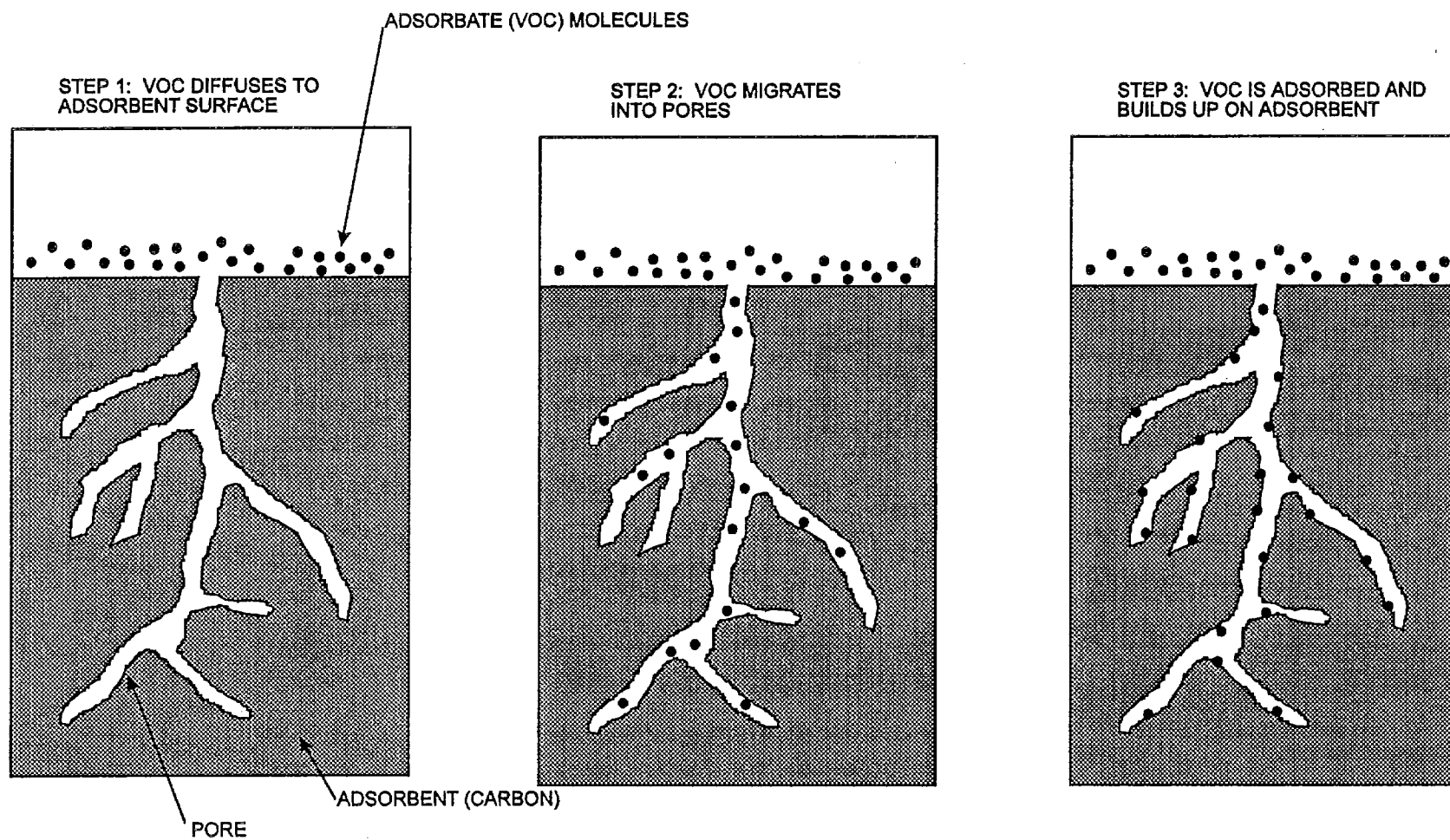


Figure 205.1
Adsorption Mechanism

200 ADSORPTION

Heel

Although the heel appears to hinder adsorption capacity, it is necessary to control the temperature of a carbon bed. Since energy is released during adsorption, the carbon gets hot. If there was no heel on the bed the temperatures in the bed could become excessive. Many VOCs are flammable so the adsorber could become potentially hazardous. When a new carbon bed is put into an adsorber, the heel must be added slowly. This is done by reducing the volume flow rate of the waste stream to the adsorber until the heel is present. In general, $2/3$ of equilibrium capacity of carbon is occupied by the heel.

Mass Transfer Zone

At any given time, a section or zone (about three inches in length) of carbon performs the adsorption of organic compounds. As the three-inch length zone of the carbon bed gets saturated with compounds, the zone where compounds collect begins to move away from the entrance of the adsorber (Fig. 205.3).⁶

Saturated zone

This zone is called the **mass transfer zone**. The mass transfer zone is the only part of the carbon bed that is removing volatiles from the waste at any time. The zone upstream of the mass transfer zone at the entrance of the carbon bed is called the saturated zone. It is the part of the carbon bed that has already reached thermodynamic equilibrium and cannot adsorb any more compounds.

Fresh zone

The zone downstream of the mass transfer zone is called the fresh zone; the carbon in this zone is still available for adsorption. Theoretically, the only compounds in the fresh zone are from the heel, but in the real world a small amount of compounds manage to get past the mass transfer zone by bypassing the carbon. The loss in working capacity from the heel is shown by Figure 205.2.

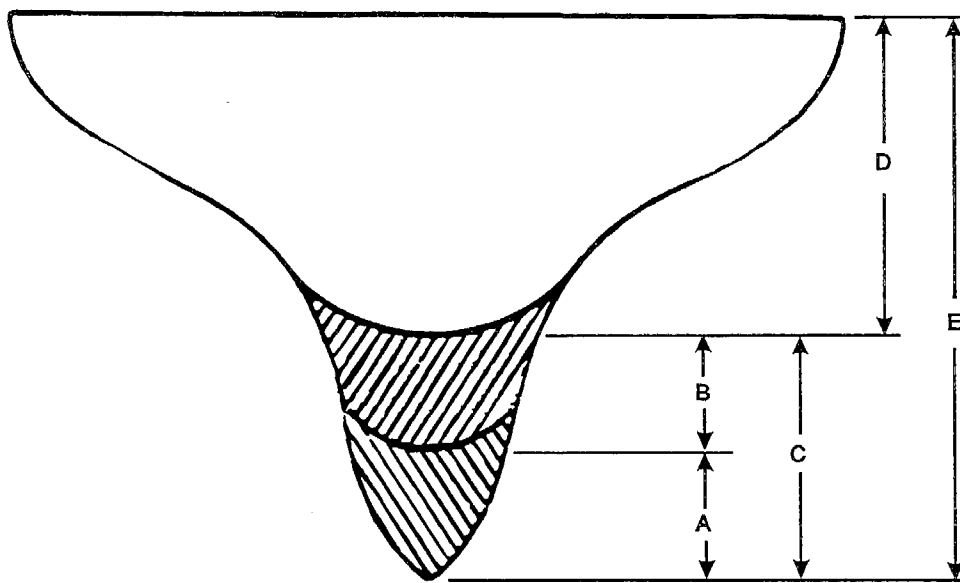
Figure 205.4 shows a graphical representation of the pore space within the different zones.⁶ In the upstream portion of the mass transfer zone, almost all the capacity of the pore space is exhausted, but on the downstream side of the mass transfer zone almost all the pore space is still available. In the fresh zone working capacity is available for adsorption, but in the saturated zone it is exhausted. The concentration of volatile organics versus distance through the bed is shown in Figure 205.5.⁶ The plot is a mirror image of the working capacity plot (Fig. 205.3).

Breakthrough

Breakthrough occurs when the mass transfer zone reaches the end of the carbon bed; the beds of an adsorption system are designed so that they undergo regeneration or are taken off-line and replaced with new carbon before the mass transfer zone gets close to the end of the carbon bed. In most designs a

200 ADSORPTION

VOC Control
Devices/
Scrubbers



A = RESIDUAL VOCs OR HEEL
B = WORKING CAPACITY
C = EQUILIBRIUM CAPACITY
D = EMPTY PORE SPACE
E = TOTAL PORE SPACE (TOTAL CAPACITY)

Figure 205.2
Pore Space Representation

200 ADSORPTION

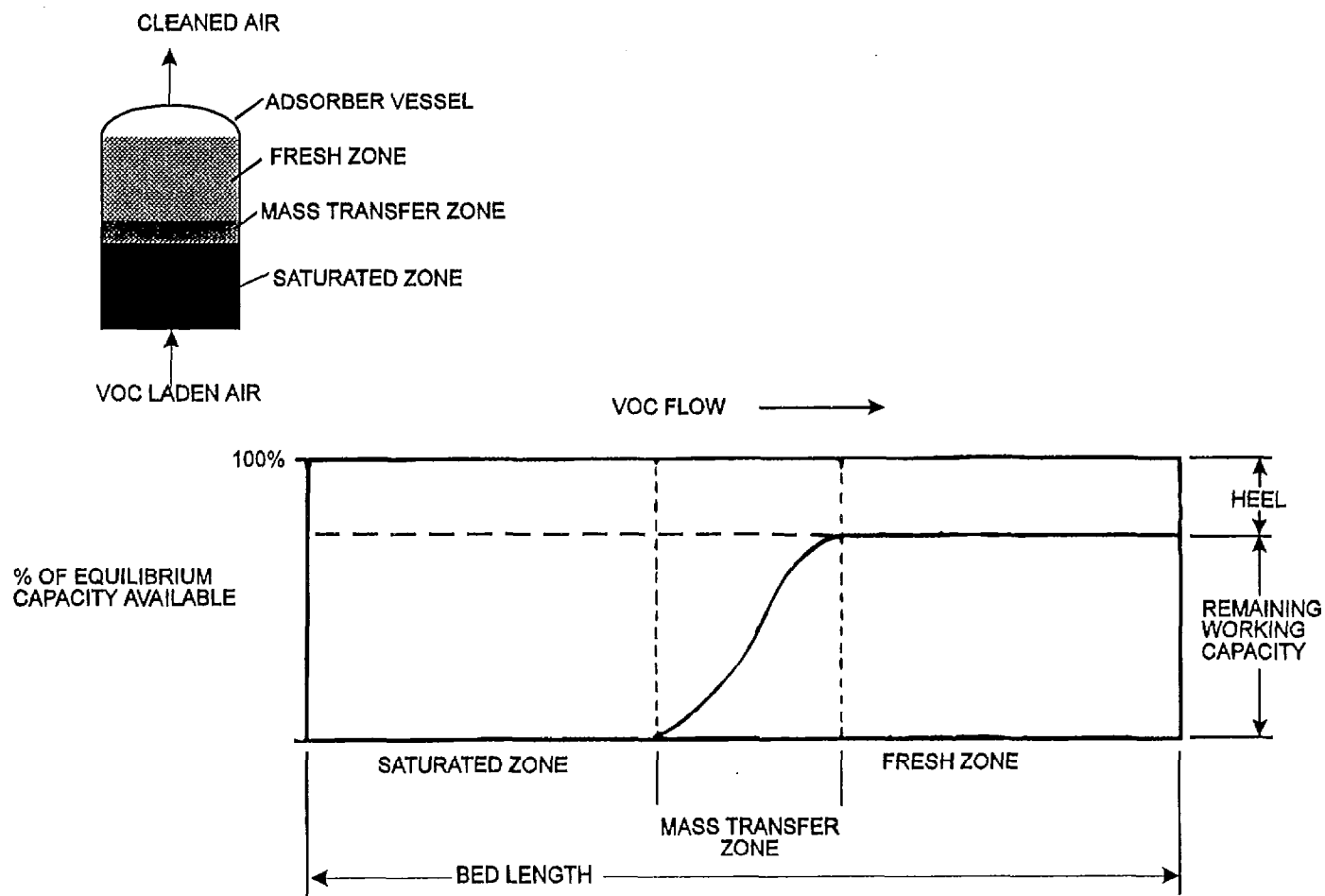


Figure 205.3 Capacity vs. Distance Through Bed

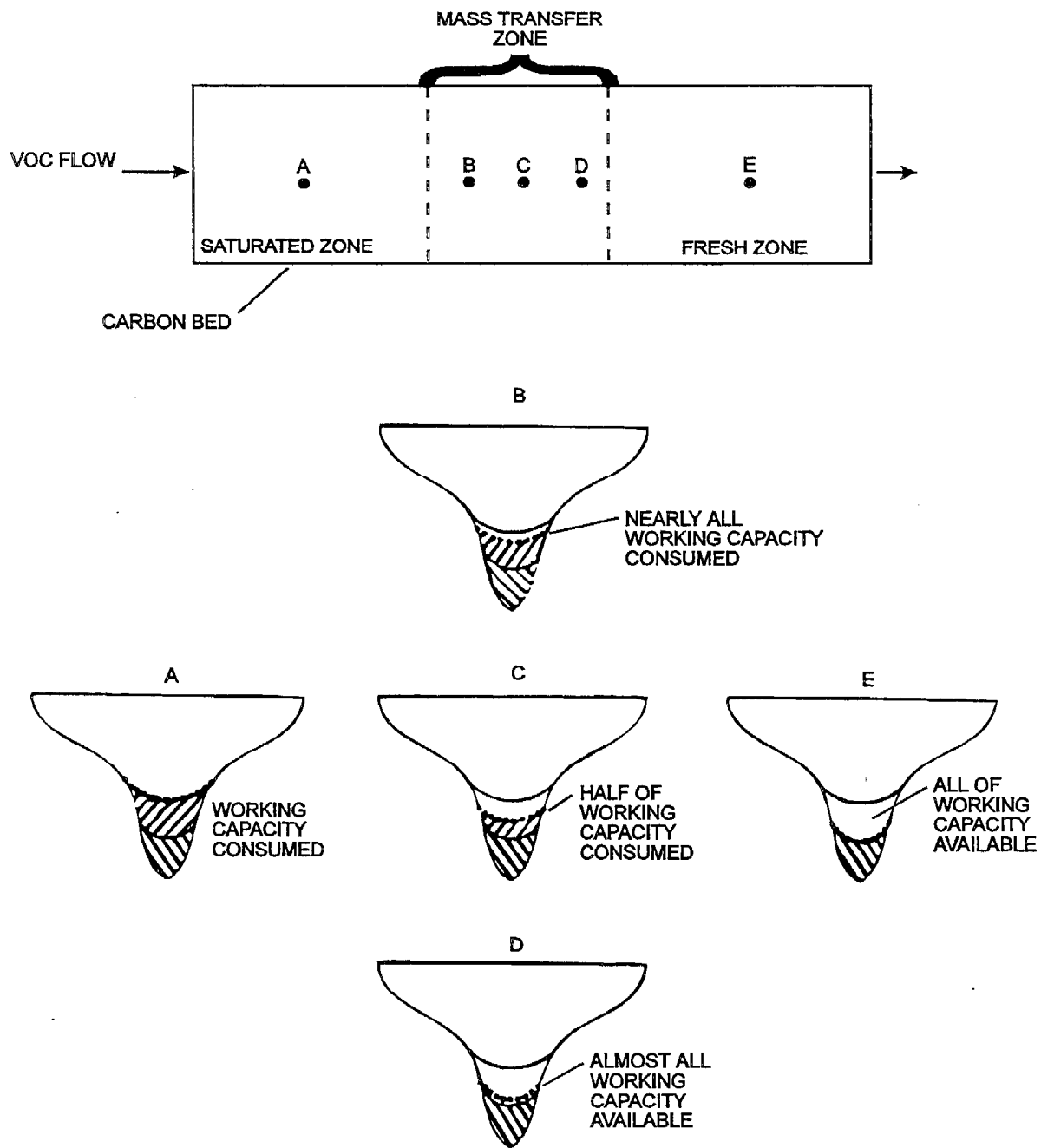


Figure 205.4 Pore Space at Different Distances Through Bed

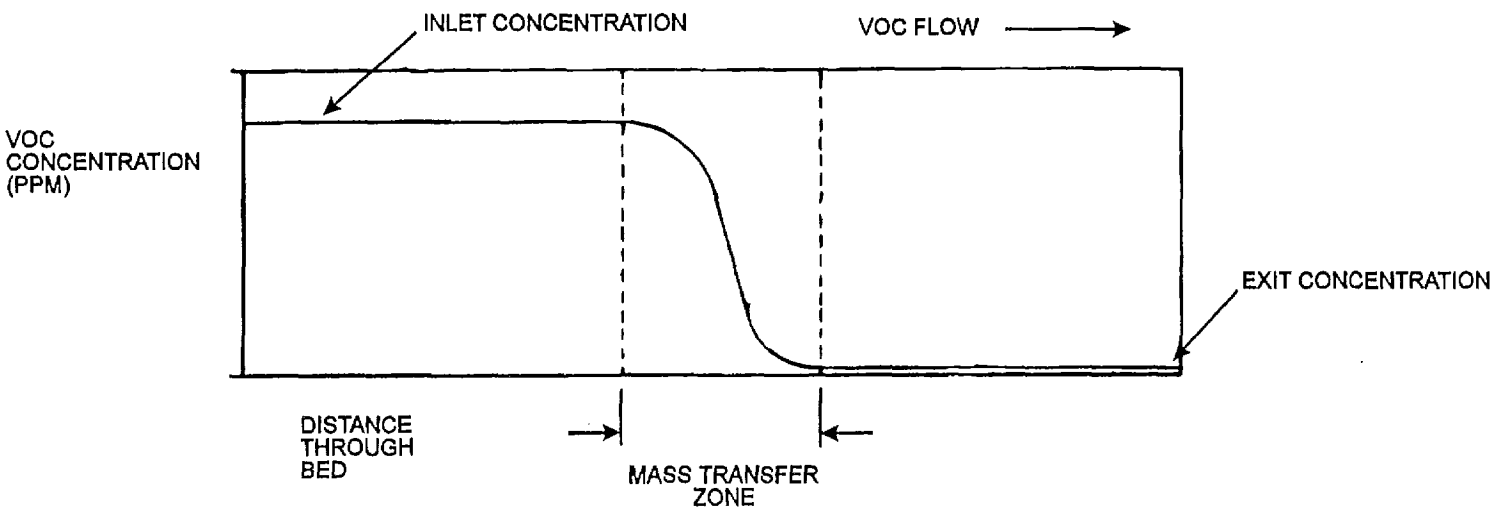


Figure 205.5 Concentration vs. Distance Through Bed

timer or monitor controls the length of time that bed adsorbs compounds. When the adsorption time on one bed is used up, the waste stream is switched to another bed and adsorption continues.

205.1 THE OUTLET CONCENTRATION CURVE

Figure 205.6 shows a drawing of a typical outlet concentration curve. At or before the breakthrough time (1) the bed that is on-line must be taken off-line and a new regenerated bed must take over the adsorption. The concentration of compounds at the exit would rise sharply and then level off as it approached the concentration at the inlet.⁶ "A" and "B" arrows show two possible ways the shape of the outlet concentration curve can change. "A" indicates a decrease in the available adsorption cycle time. An "A" shift (to the left) does not have a large effect on the collection efficiency of compounds, but the bed will have to be regenerated or replaced more often, lowering the overall efficiency of the system since more regeneration energy is required or more carbon must be used because of more frequent replacements.

A Type "A" shift will significantly affect the collection efficiency if a bed is left on-line after breakthrough has occurred. Collection efficiencies tend to vary more when a bed has been left on-line after breakthrough has occurred.⁶

An "A" shift (to the left) indicates a change in working capacity of the carbon for a given adsorbate. Working capacity is a function of fouling and equilibrium conditions (temperature, pressure, and partial pressure of the adsorbate) for a given set of operating conditions (regeneration time, adsorbate content, etc.). Therefore, changes that affect the working capacity cause type "A" shifts in the breakthrough curve.⁶

When the outlet concentration curve shifts in the "B" direction (upward), two possible problems could be occurring. First of all, a portion of the inlet stream could be short circuiting, or channeling could be occurring. Secondly, a larger heel could be present at the last few inches of the bed. The amount of the heel is a function of the regeneration time, temperature and flow.

Shifts in the
Outlet Curve

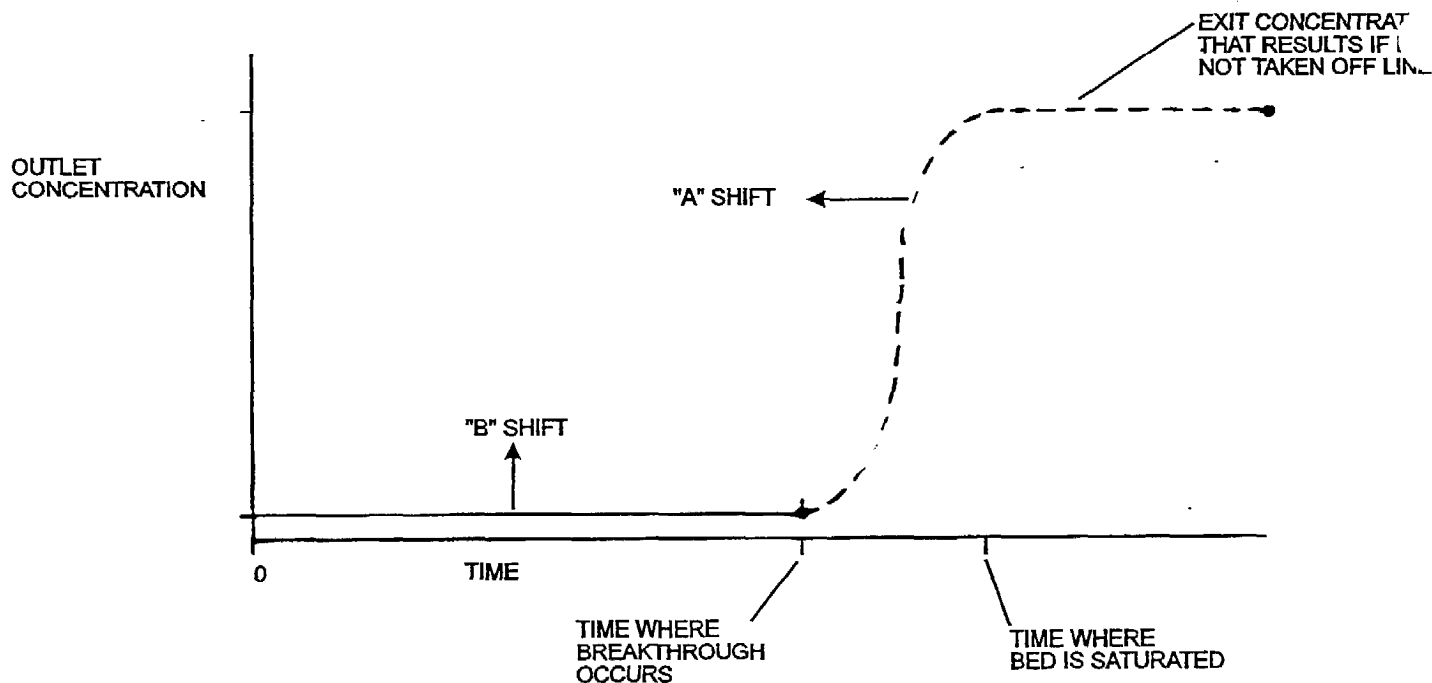


Figure 205.6 Outlet Concentration Curve

206 REGENERATION OF CARBON BEDS

Regeneration (also called desorption) of a carbon bed is an important step in the carbon adsorption systems that use it. All of the VOCs are never completely removed from carbon beds after regeneration. All compounds are not removed from the carbon because a lot more time and energy would be required to totally remove all the adsorbate and a heel is required to control the temperature. It is more economical to leave some of the adsorbate behind after each regeneration. Longer regeneration times or higher regeneration temperatures will reduce the heel. The working capacity of a carbon bed is the difference between the adsorption capacity and the heel (residual compounds remaining in the bed).

In some carbon adsorption systems, the carbon may not be regenerated because it is not economical to do so. For very small systems, such as those used in dry cleaning, the exhausted carbon is usually removed and regenerated off-site. In a small system the amount of recovered solvent is relatively low and may not be able to offset the expense of regeneration. Large systems recover more solvents, making it economical to recover them.

200 ADSORPTION

VOC Control Devices/ Scrubbers

Pressure, heat or a combination of both is generally used to remove VOCs from activated carbon. The energy required to remove compounds from a carbon bed is generally proportional to the latent heat of vaporization of the material in the carbon bed.⁴ Larger compounds with higher molecular weights will tend to have higher latent heats of vaporization, higher boiling points and will be more difficult to remove from carbon beds. For example, butane (C_4H_{10}) is easier to remove from carbon than xylene (C_8H_{10}).

In order to remove volatile products from carbon that are not miscible in water, steam may be injected through the carbon bed in the opposite direction of the waste stream flow. Since many VOCs do not mix with water, VOCs can readily be separated by gravity from steam and water after it exits the bed. Steam heats the carbon bed, volatilizing the VOCs within it, overcoming the physical van der Waals forces binding them to the carbon. The velocity of the steam helps carry volatile compounds out of the bed. Nitrogen can be used as a stripping agent for carbon beds to remove compounds that are miscible in water.

Steam Regeneration

In order to remove volatile compounds from the water and steam, it is put through a decanter where volatile compounds are removed. After regeneration the bed is sometimes dried with heated air. A small amount of moisture on the bed can be beneficial because it makes the bed behave as a heat sink during adsorption.⁶ Too much water in the bed will hinder adsorption. The regenerated bed is cooled by passing ambient air through it. In some designs the cooling and drying is performed by a single air stream. The air is usually directed in the bed opposite the direction of the waste stream flow. The flow of air can also help remove trace amounts of VOCs.

A problem with steam regeneration is that the carbon may have to be dried in order to provide efficient adsorption. Additional time is required for the drying step. Steam can also be used in a heat exchanger to heat air for regeneration to keep the carbon dry.

Some carbon adsorption systems are regenerated by putting a vacuum on the carbon beds. Putting a vacuum on the system volatilizes the compounds in the carbon bed because of the extremely low pressure on the bed. Vacuum pumps draw a vacuum on the carbon bed, then draw VOCs to an area where

Vacuum Regeneration

200 ADSORPTION

they can be collected. Using a vacuum is a good way to remove highly volatile compounds from carbon beds. A vacuum also works on adsorption systems that can handle higher amounts of residuals in the carbon bed.

The advantage of using a vacuum for regeneration is that the products removed from the carbon bed will be purer, unlike regeneration with steam. On the other hand, the equipment costs of the large pumps required for vacuum regeneration can be very high.

207 CARBON ADSORPTION SYSTEM DESIGN CONSIDERATIONS

The conditions of the waste stream entering an adsorber are first considered for the design of a carbon adsorption system. The type of compounds in the waste stream and the relative humidity of the waste stream are also important. The average temperature, range of temperature, and adsorbate concentrations are also major design considerations.

Porosity

The carbon for an adsorber is chosen based on its porosity. A majority of the pores in the carbon should be smaller than approximately twice the diameter of the adsorbate molecules so adsorptive forces will be maximized.⁶

Area and Velocity

After the carbon is chosen, the bed area is calculated. The cross-sectional area of the bed can be calculated from the velocity of the waste stream and the volume flow rate. The volume flow rate (Q) = (Area)(Velocity). The velocity of the waste stream through a system is usually desired to be between 20 ft/min and 100 ft/min. If the velocity is too low the waste stream will not distribute properly within the carbon bed. If the velocity is too high, system power use is excessive and bed pressure drops and the discharge head (pressure) will be too high.

Bed Length

The length of the bed must be longer than the mass transfer zone or breakthrough will occur almost immediately. The length of the bed is limited by the pressure drop. The longer the bed the higher the pressure drop will be in the adsorber. Within these constraints the bed length is more precisely determined by the volume of carbon required for each adsorption cycle. The volume of carbon required depends on the solvent mass loading, the carbon's density, the carbon's working capacity, and the available adsorption time. The

200 ADSORPTION

VOC Control Devices/ Scrubbers

solvent mass loading depends on the characteristics of the waste stream and the carbon density depends on the type of carbon chosen. The working capacity and the available adsorption time are interrelated and are determined by the particular carbon, design temperature, adsorbate concentration, specific compounds present, superficial velocity, and regeneration parameters. The time required for adsorption must be greater than the time required for regeneration of the carbon beds.⁶

Multiple organic compounds in the waste stream are another design consideration. More volatile, less strongly adsorbed compounds will be displaced by more strongly adsorbed ones. In the front of the mass transfer zone a wavefront of compounds with higher volatility will be created. The carbon bed must be designed so it is regenerated before the advancing wave of highly volatile compounds breaks through the end of the bed.

Multiple Organic Compounds

The steaming requirements for adsorbers that use steam are also a part of the initial system design. The longer a bed, the more regeneration it will require. The longer a bed is regenerated, the smaller the heel will be and the more working capacity the system will have. The longer the regeneration time is, the higher energy costs will be. Figure 207.1 shows how working capacity varies with steam flow.⁶ As more steam is used the increase in working capacity begins to flatten out. The steam flow in the regeneration portion of an adsorption system should be countercurrent to the direction of the waste stream flow because this design helps lower the concentration of VOCs that escape out the end of the adsorber. This design also lowers the heel in the end of the adsorber which is closest to the outlet to the atmosphere (Fig.207.2).⁶

Steaming Requirements

Fouling of the carbon bed from particulates, high molecular weight compounds, and chemicals that react with the carbon bed is also a design consideration. Compounds that foul the carbon bed reduce the life of the bed and require a longer regeneration period. Fouling also reduces the working capacity of the adsorber. Some higher molecular weight compounds do not desorb from the carbon very well. If higher molecular weight compounds are being adsorbed the volume of the carbon adsorber design can be increased. The regeneration time designed into the system may also be increased.

Fouling

Figure 207.3 illustrates the typical adsorption/desorption cycle times of a typical system with two adsorbers⁶. Only one bed desorbs at a time. At time = 0 bed #1 begins adsorption and continues adsorption for 90 minutes, but bed #2

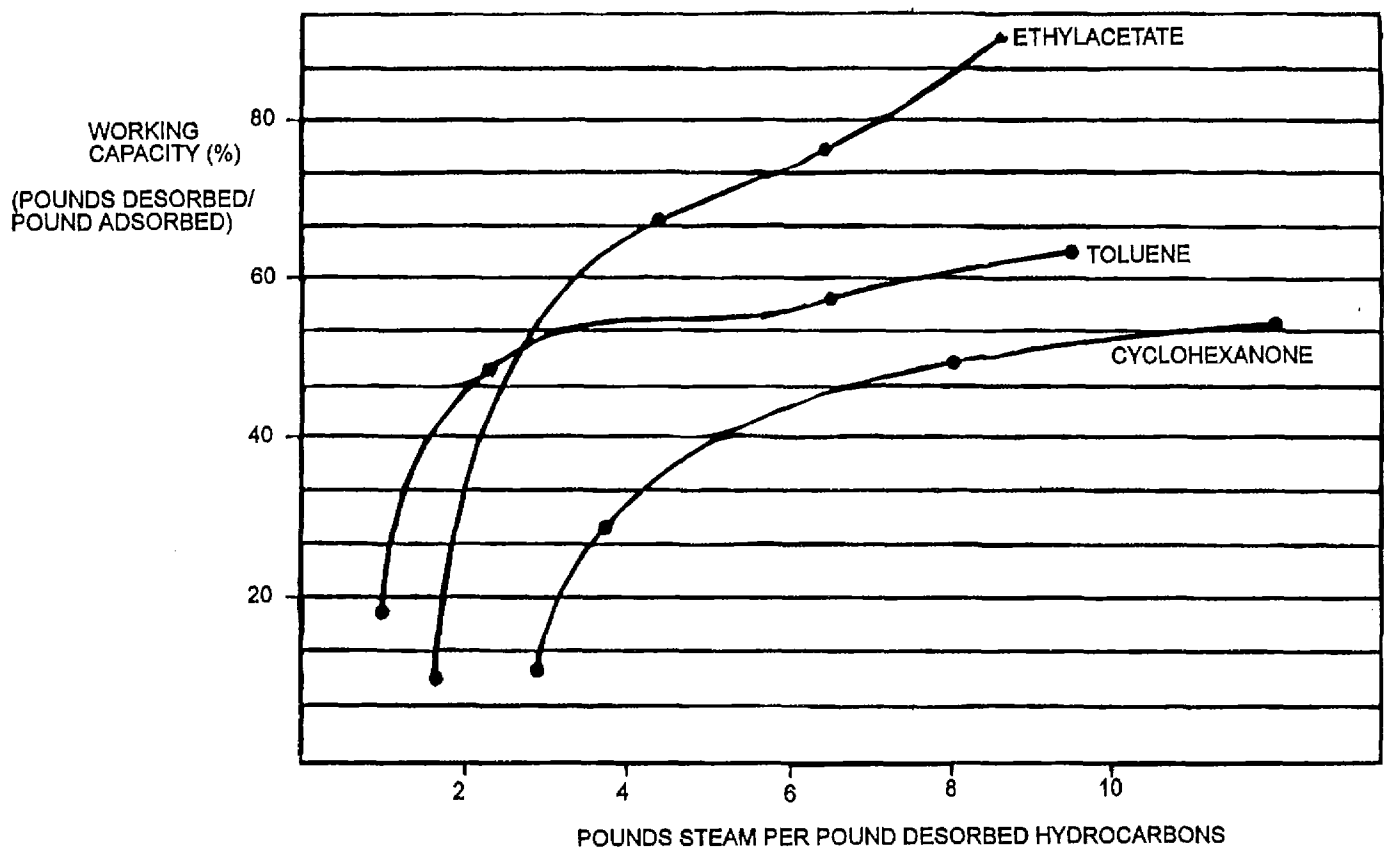


Figure 207.1 Pounds of Steam from
Regeneration vs Working Capacity

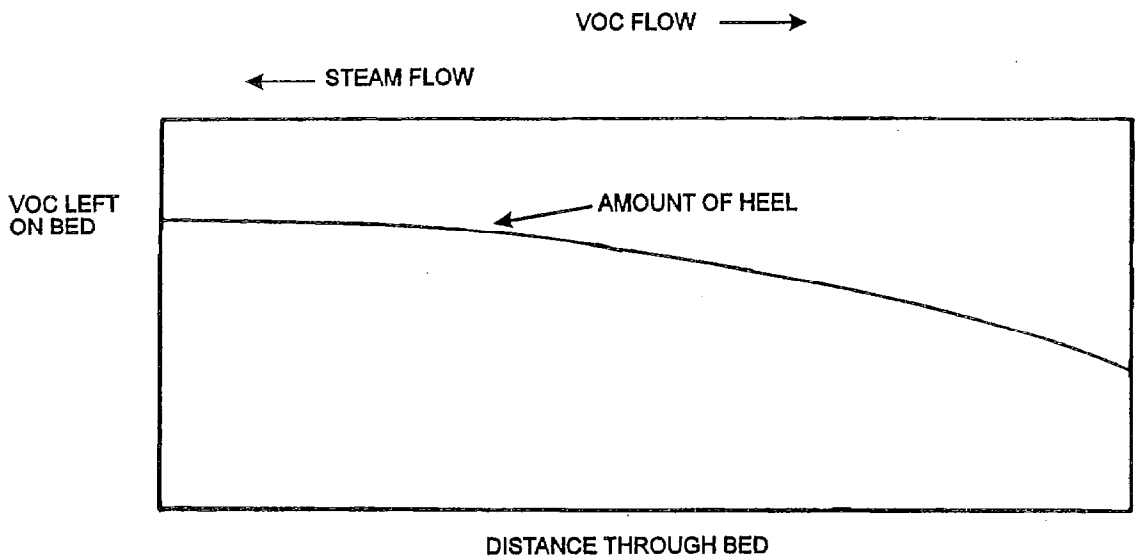


Figure 207.2 VOC Concentration vs. Distance Through Bed After Regeneration

**Timers and
Monitors**

begins regeneration and continues regeneration for 60 minutes. Bed #2 goes into the standby mode after 60 minutes and at time = 90 minutes bed #2 begins to adsorb and bed#1 regenerates. After a standby time of 30 minutes for bed #1, the cycle starts all over again.

Timers and monitors are the two different methods used to control the adsorption time of an adsorber. An adsorber can be designed so that a timer takes an adsorber off-line before breakthrough occurs. A timed system will not utilize the entire carbon bed because the timer takes the bed off-line before the mass transfer zone gets to the end of the bed. 25% or more of the working capacity of the carbon bed may not be utilized since the capacity of the bed will decrease over time.

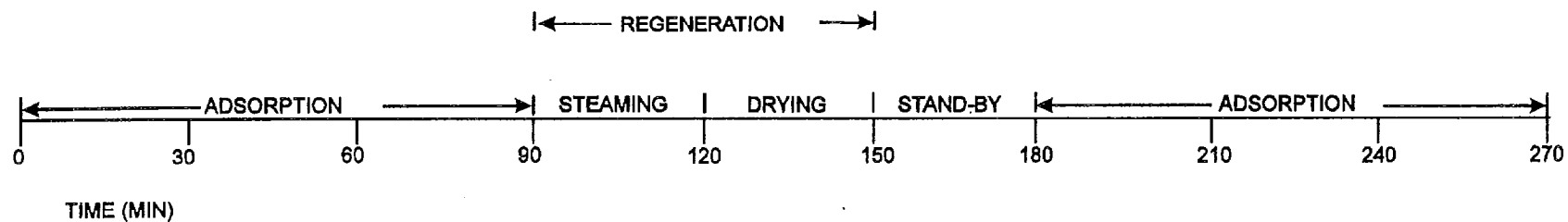
On the other hand a monitor can sense when breakthrough begins to occur. A monitor can guard against breakthrough and the total working capacity of the bed will be available. Timers are better for systems that do not have substances in their waste streams that promote fouling. Timers work well on systems that handle a constant load from the waste stream. Some systems may use both timers and monitors.

Channeling

Channeling is a problem that an adsorber design must be able to handle. Channeling occurs when one portion of the carbon bed receives more compounds than other parts of the bed or when a portion of the waste stream bypasses the bed entirely. Channeling is avoided by properly designing the inlet of an absorber to distribute the waste stream in the bed. Some designs minimize channeling by using distribution baffles to properly distribute the waste stream at the correct velocity.⁶

Channeling can also occur during regeneration. If steam is not distributed evenly within an adsorber, parts of it will not be properly regenerated. Areas within the carbon with higher and lower concentrations of compounds will be created.

BED #1



BED #2

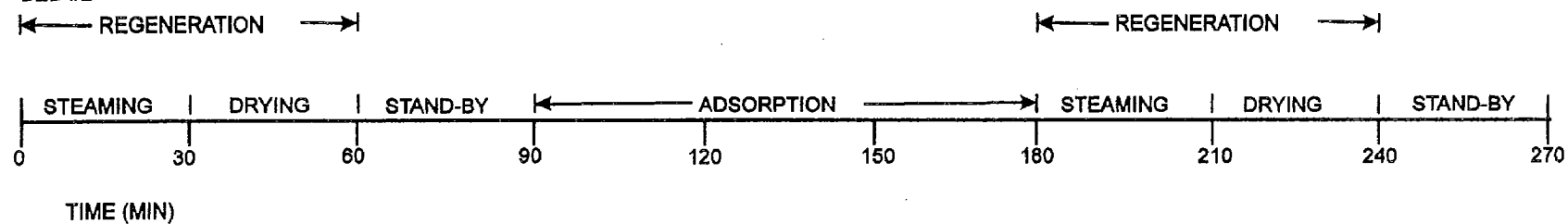


Figure 207.3 Adsorption/Desorption Cycle Times

208 FACTORS AFFECTING CARBON ADSORPTION EFFICIENCY AND WORKING CAPACITY

A fixed amount of organic vapor can be adsorbed on the carbon in a carbon adsorber. The limit is a function of the amount of carbon in the bed, the carbon characteristics, the organic vapor concentration, the chemical characteristics of the organic compounds being adsorbed, and the gas stream temperature. The more carbon that is in a carbon bed the higher its capacity. Adsorption capacity tends to increase as the concentration of the organic compounds in the waste gas stream increases.

Some daily variations in process conditions may affect adsorber performance. Temperature, relative humidity, flow rate, and bed fouling are daily variables that may affect performance. Changes in the solvents in the waste stream can also change performance.

208.1 TEMPERATURE

The lower the temperature of a waste stream, the better VOCs can be adsorbed from it. Lower temperatures reduce the movement of molecules, allowing intermolecular forces to keep more VOCs on the surface of the carbon. Temperature changes as small as 15°F can have a significant impact on the capacity of carbon adsorbers. It is best if the waste stream is less than 120°F. Unfortunately, as adsorption progresses in an adsorber, heat is released and the carbon's temperature rises.

The temperature in an adsorber may be changed by a change in the inlet stream temperature, a change in the exothermic chemical reactions within the adsorber, a change in the flow rate or a change in the regeneration step. If, for example, the waste stream temperature goes up, the adsorber temperature will tend to rise. Since adsorption is an exothermic reaction, an increase in the solvent load to an adsorber can increase the temperature. Lowering the flow rate of the waste stream decreases the solvent load per unit time and will help lower the temperature of the carbon. Furthermore, some compounds may react directly with the carbon bed, reducing or increasing the temperature. Ketones, for example, are known to react with the carbon bed. A system handling ketones must have adequate air flow to remove the heat of chemical reactions to keep the temperature from getting too high. Some

systems handling ketones will have temperature sensors to detect high temperatures in different regions of the carbon bed, so protective action of the bed can be initiated.

Figure 208.1 illustrates what happens to carbon adsorption working capacity as the temperature is varied.⁶ As the temperature of the adsorber increases the working capacity decreases and the outlet concentration curve will shift to the left in the "A" direction (Fig.205.6). An increase in the temperature of an adsorber will require changes in the times for adsorption and desorption. Regeneration would have to be performed more often on the carbon beds, since breakthrough would occur more rapidly. With higher temperatures, cycle times can be adjusted to achieve the same removal efficiency as when temperatures were lower, but more energy may be used because of the increased number of regenerations. If the temperature of the bed during adsorption rises to a point close to the temperature of the bed during steaming, the removable efficiency will drop.

Changes in adsorption temperature do not cause a "B" shift in the breakthrough curve because the outlet concentration at the beginning of the cycle is primarily a function of the heel remaining in the last few inches of the bed.⁶ The amount of heel in the bed is established by the regeneration conditions.

Temperature changes in an adsorber from the inlet stream can be eliminated by the use of a heat exchanger. The temperature in an adsorber can be kept down by allowing cooling during or after regeneration and avoiding adsorption periods that are too long. Higher inlet velocities and controlling the relative humidity will also lower heat buildup.

208.2 RELATIVE HUMIDITY

Waste streams with high relative humidities over 50% can have an adverse effect on the capacity of carbon to adsorb some VOCs.⁴ Relative humidity is a term that shows the amount of water in the air. Relative humidity (ϕ) is defined as the partial water vapor pressure (p_w) (the pressure of water in an air water mixture) divided by the saturation pressure (p_{sat}) (the pressure at which an air water mixture is saturated) or $\phi = p_w/p_{sat}$.²

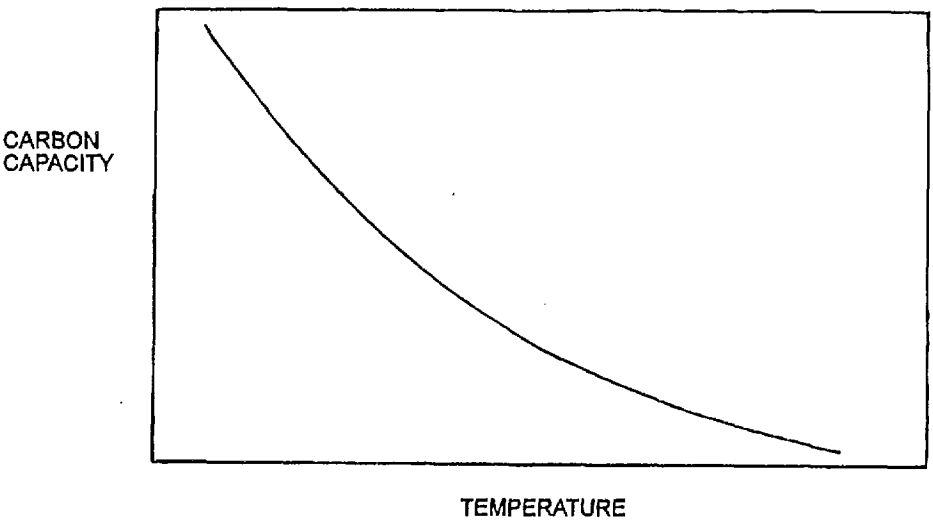


Figure 208.1 Adsorption Capacity vs
Temperature at Constant Pressure

200 ADSORPTION

VOC Control Devices/ Scrubbers

At high relative humidities above 50%, a significant amount of water begins to condense within the microporous structure of the carbon bed. The higher the relative humidity is the more the pores of the carbon will fill with water. High relative humidities do not affect the amount of the heel within the carbon bed.

A small amount of water in the carbon bed can help improve carbon adsorption. Water on the bed behaves as a heat sink and helps control the temperature.

The relative humidity of a waste stream can be reduced by heating the stream 20-30°F, but with higher temperatures the adsorption capacity declines. The relative humidity may also be reduced by first cooling a waste stream to condense out the moisture and then reheating it. Diluting the inlet stream is another way of overcoming the effects of high relative humidities.

Activated carbon can still be effective at controlling VOCs in humid environments. Activated carbon is made primarily of neutral atoms that present a nonpolar surface. Water molecules are polar molecules and tend to be attracted to each other and do not compete as strongly for the nonpolar sites in the carbon bed as VOCs.⁷ Carbon beds can also be designed to remove contaminants from water. Liquid phase carbon is designed to remove contaminants from water while gas phase carbon is made to remove contaminants from gas streams.

208.3 CONCENTRATION, TYPE OF VOC AND IMPURITIES

The adsorption characteristics of compounds are measured by their molecular weight, boiling point, polarity, refractive index, and solubility in water. Heavier VOCs, which are larger molecules and have a bigger molecular weight, will shorten the life of a carbon bed. Larger molecules, especially those with a molecular weight over 142, are more difficult to remove from carbon beds. Compounds with a high vapor pressure (low boiling point) do not adsorb as easily. Nonpolar compounds with a high light refractive index tend to adsorb more easily.⁶ During the regeneration cycle, larger VOC molecules will tend to get trapped in the carbon pore structure. After regeneration more residue will be left behind, leaving less space to adsorb VOCs.

200 ADSORPTION

If steam is used for regeneration, a small amount of condensate water will be left over in the carbon bed. Compounds that are soluble in water will dissolve in the condensate. When the adsorber is brought on-line, the condensate and compounds will evaporate and the outlet concentration will increase for a short period of time.

Air pollution control with carbon adsorption generally works well for VOC concentrations below 700 ppmv and as high as 25% of the lower explosive limit.⁴ (See Table 502.2 for common lower explosive limits.) In general, adsorption capacity tends to increase with increasing solvent concentrations. In many instances it is profitable to recover a VOC, but if the concentration of the solvent is far below 700 ppmv, it may not be economical to recover a solvent. When solvent recovery is performed and the concentration of solvent is very low, more regeneration products must be used and the amount of VOCs remaining in each adsorber after each regeneration will increase, leaving less carbon available to capture VOCs.

Carbon adsorption works best when a single compound in a waste stream is being collected. When more than one compound is present in a waste stream, the most volatile one will tend to revaporize.

Methane and Ethane

The presence of methane or ethane in a waste stream can be a problem for carbon adsorbers. Methane, the main gas component in natural gas, will not adsorb onto a carbon bed because it has such a low molecular weight and low boiling point. Ethane will adsorb on to carbon some but a lot of it will pass through an adsorber. If a waste stream has methane or ethane, it may register as VOC emissions for a continuous emission monitor. Methane is not considered to be a VOC. The EPA definition of VOC does not include ethane, but the Air Resources Board definition for ROC (Reactive Organic Compound) includes ethane as a VOC.

The presence of methane and ethane in organic liquids in the petroleum industry has been a problem in the past. Natural gas has been used for gas blanketing storage tanks and natural gas will dissolve into gasoline and other organic liquids. The primary methods available for controlling methane and ethane are refrigeration and incineration. Incineration is usually used, since these compounds have very low boiling points.

208.4 FOULING

Fouling of carbon beds is caused by impurities in a waste stream adversely affecting carbon adsorption systems. Sulfates, dust, ash and other particulates will tend to "plug up" carbon beds, reducing the working capacity, the number of adsorption sites, and pores in the carbon. A decrease in the working capacity will cause breakthrough to occur more rapidly, but it will cause little or no change in the removal efficiency (when costs and energy use are considered the overall efficiency may decrease). The outlet concentration from an adsorber is not affected by fouling, but it will increase the costs of running an adsorber.⁶ Fouling also has no effect on the amount of heel. Once the shortened length of time of the adsorption period from fouling begins to interfere with the regeneration period, the carbon in the adsorber must be replaced.

In order to counter the effects of fouling, the temperature or steam flow rate can be increased during regeneration. This will decrease the heel left in the carbon. Over time, changes in the regeneration cycle will not prevent the effects of fouling and the carbon will have to be replaced.

208.5 VOLUMETRIC FLOW RATE

When the superficial velocity of a waste stream into an adsorber is increased, the volume flow rate also increases. Increasing the volume flow rate of a system causes the length of the mass transfer zone to increase. With a higher superficial velocity, carbon pellets are exposed to compounds for a shorter period of time and the amount of VOCs removed per unit area decreases. Different flow rates have little effect on short term removal efficiency. When the flow rate of a typical adsorber was varied from 45,000 scfm to 25,000 scfm, the removal efficiency varied less than 0.5%.⁶ The volume flow rate does not affect the heel, so there is no B shift in the outlet concentration curve.

208.6 CHANNELING

Channeling occurs when some part of the waste stream entering an adsorber bypasses the carbon bed or a portion of the bed gets more compounds than the rest of the bed. Channeling can also occur when some portions of the bed are

200 ADSORPTION

regenerated more than others. Steam for regeneration must be evenly distributed in an adsorber. If channeling occurs there may be a gradual increase of compounds emitted from the adsorber during the adsorption cycle resulting in an elevated level of emissions.

208.7 REGENERATION

When steam is used for regeneration, the steaming temperature, duration and rate have a large effect on adsorption capacity. The temperature of the steam used can be a difficult parameter to change in a system. A carbon's adsorption capacity decreases over time; gradually increasing the steam use per desorption cycle can be done to momentarily prevent the drop in working capacity. Adequate time is required to desorb pollutants from the activated carbon. Increasing the steaming rate without allowing sufficient time will still not remove the adsorbate from deep within the pores of carbon.

209 MAIN TYPES OF CARBON ADSORPTION SYSTEMS

Most carbon adsorption systems can be broken into three parts: the pretreatment section, the carbon adsorber, and the recovery or waste section.

Pretreatment Section

In the pretreatment section the waste stream is run through filters to remove particulates and other materials from the waste stream that are detrimental to carbon beds. If the temperature of the waste stream is too high, it will be reduced in the pretreatment section by heat exchangers.

Adsorber Section

After the pretreatment section, volatile compounds are removed from the waste stream by the carbon. Carbon adsorption systems are usually equipped with two or more adsorbers so that one or more adsorbers can be on standby, regenerating, or being replaced with new carbon while another bed is adsorbing compounds.

The carbon is usually installed in adsorbers in separate sections or on trays, allowing for easy installation and exposing a large surface area to the waste stream. This also allows operators to replace carbon sections in an adsorber that have their adsorption capacity exhausted. The carbon in an adsorber is often gauged in pounds of carbon.

200 ADSORPTION

VOC Control
Devices/
Scrubbers

In the recovery or waste treatment section (many carbon adsorbers don't have regeneration systems) organic compounds are removed from the carbon. If compounds are removed from the carbon by steam, the steam is condensed and decanted. In the decanter the condensed steam and compounds are separated from each other. Compounds may also be recovered from the carbon by a vacuum.

Recovery/
Regeneration

209.1 OPEN CARBON ADSORPTION SYSTEMS

Open carbon adsorption systems are commonly used for solvent recovery and air pollution control. In an open system the waste stream flows through the adsorber and cleaned air flows out into the atmosphere. Open systems can vary widely in size from adsorbers with several hundred pounds of carbon to those with over 40,000 pounds of carbon. The flow rates of open systems can vary between 50 and 10,000 scfm (standard cubic feet per minute, i.e. the flow rate at standard temperature and pressure).

209.2 CLOSED CARBON ADSORPTION SYSTEMS

In a closed carbon adsorption system, the cleaned waste stream is reused to continue pollution control or the manufacturing process. In many closed systems the cleansed waste stream is returned to be used as a stripping agent. In some wastewater treatment systems, the air stream from an adsorber exhaust stream is pumped to a vessel where the wastewater is saturated with the air stream. This type of system is common in refineries and other petrochemical plants. The air is pumped into the stripper vessel by a compressor and it is suddenly released into the stripper vessel at a much lower pressure. Microscopic bubbles form in the wastewater and carry contaminants to the surface of the wastewater where they can be removed. The air stream is then dried by being run through a condenser or chiller, which cools the air stream to condense out liquid water. It may then be run through a heat exchanger to remove more moisture. The dehumidified stream, which is still contaminated with VOCs, is then again run through an adsorber bed. Then the air goes back to the stripper vessel again.

200 ADSORPTION

Rotary Carbon Adsorber

209.3 MOVING BED AND FIXED BED SYSTEMS

Although most carbon adsorption systems have a fixed (non-moving) carbon bed, one common type of moving bed system is the rotary or wheel type of carbon adsorption system. In the rotor system the adsorber bed is shaped like a wheel. One type of rotor design has a corrugated wheel with a honeycomb structure coated with powdered activated carbon. Another variation of this design is a wheel with separate carbon sections around the circumference of the wheel. This type of design allows for easy installation of carbon in the wheel (Fig. 209.1).

The wheel rotates very slowly (typically 1 to 2 rev/hr), as a duct passes the waste stream containing VOCs through the wheel. Volatile compounds are removed from the air by adsorption. A duct is mounted outside the wheel to provide for hot desorption air. Another separate duct may be mounted to provide cooling of the section of the wheel that has just been desorbed. These ducts are sealed against the wheel to prevent leakage and mixing of the streams. Hot air is constantly passed through the desorption zone of the wheel, continually removing compounds from one section. Cool air is usually used to reduce the bed's temperature after desorption.

At first glance, the system may seem impractical in that the waste is passed from one air stream to another, but there is a difference between the waste stream and the exiting desorption air. The desorption air stream has a volume flow rate that is 1/5 to 1/15 of the original waste stream and a VOC concentration 5 to 15 times the original waste stream. VOCs in the desorption stream can then be destroyed by combustion or recovered by refrigeration.

Rotor systems have been used for controlling vapors from spray booths, semiconductor manufacturing, wood processing, pharmaceutical operations, and aerospace industries.⁴

Fluidized Bed Carbon Adsorber

Another variation consists of a partially fluidized bed carbon adsorber. In this system, activated carbon granules flow downward by gravity through a channel, while the waste stream flows perpendicular to the adsorbent in a cross-flow configuration. The adsorbent is then regenerated and returned to the top of the adsorption system so it can flow through the channel again. This type of system

200 ADSORPTION

VOC Control
Devices/
Scrubbers

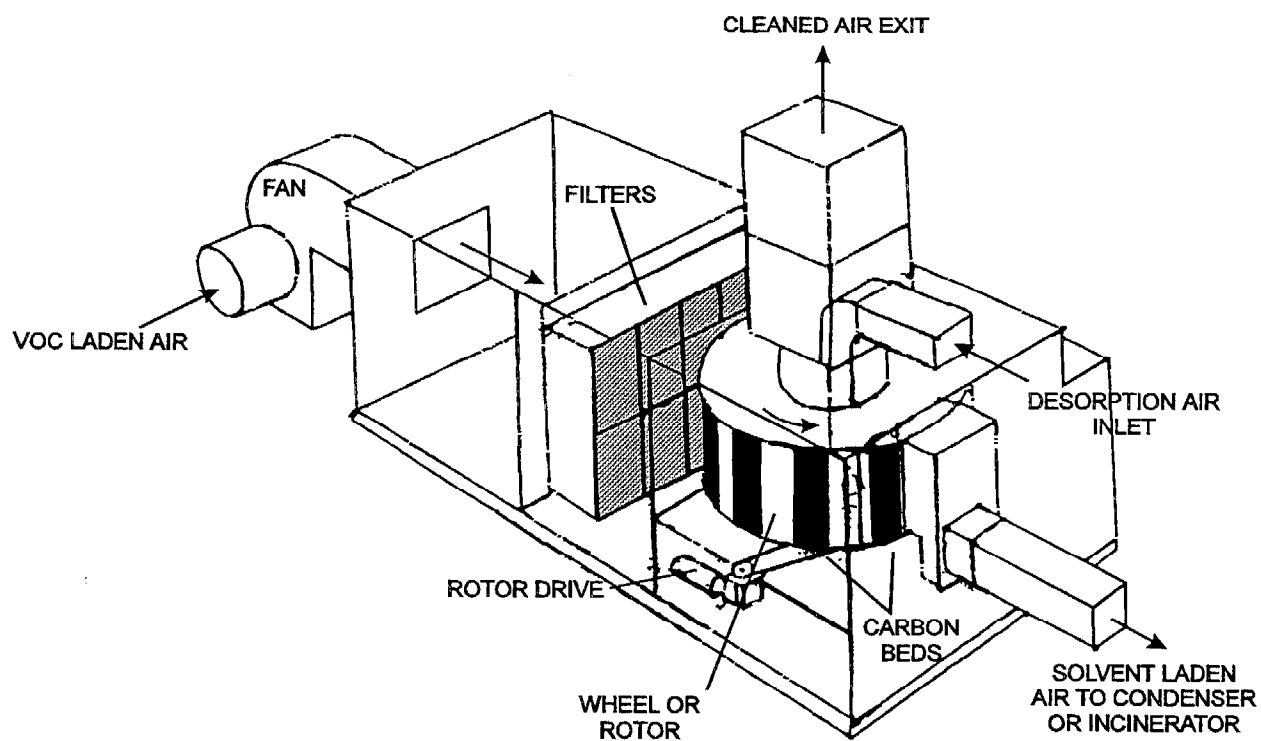


Figure 209.1 Rotary Carbon Adsorption System

200 ADSORPTION

creates good contact between the waste gas and adsorbent, but the wear on the adsorbent from the movement through the system shortens the life of the adsorbent.

210 BULK PLANT ADSORBER AND ABSORBER

Figure 210.1 shows a system that is often used to control gasoline vapors at a gasoline bulk plant. This system uses a vacuum for regeneration and also contains an absorption system.

When a truck comes to fill its tanks at a bulk plant, the vapor space within the tank is transferred to the storage tanks of the bulk plant, while the liquid gasoline is transferred to the tank of the truck. Many bulk plants have a tank designed to hold the vapors, known as a "vapor holder" or lifter roof tank. The roof of the tank rises as more vapor enters it from the continual loading of trucks. When the level of the vapor holder tank gets to a certain level, valves open and allow vapors to enter the adsorption system. The pressure within the storage tank pushes the vapor across the carbon, removing gasoline vapors. The cleaned gas then exits through the top of the adsorber.

The regeneration is controlled by a timer. When the regeneration begins, the vapor stream is switched to the other bed. Vacuum pumps then pull a vacuum on the adsorber, causing the collected gasoline vapors to be revolatilized and removed from the carbon bed. The vapors are sent to the absorber, where the vapor is absorbed by a gasoline spray and packing in the absorber, making the vapor reenter the liquid phase. Collected gasoline is then routed back to the storage tanks.

Glycol is used to provide the sealing for the vacuum pumps so the pumps can create a large vacuum. Glycol also resides in the absorber but it is heavier than the gasoline. The gasoline floats on top of the glycol and a weir is used to separate the gasoline from the glycol. The glycol is also run through a heat exchanger to cool it so the pumps will operate properly. The pumps increase the glycol temperature approximately 18° F.

Excessive amounts of moisture or glycol that gets into the carbon of the adsorbers will adversely affect the collection of vapors.

Vapor Holder
Tank

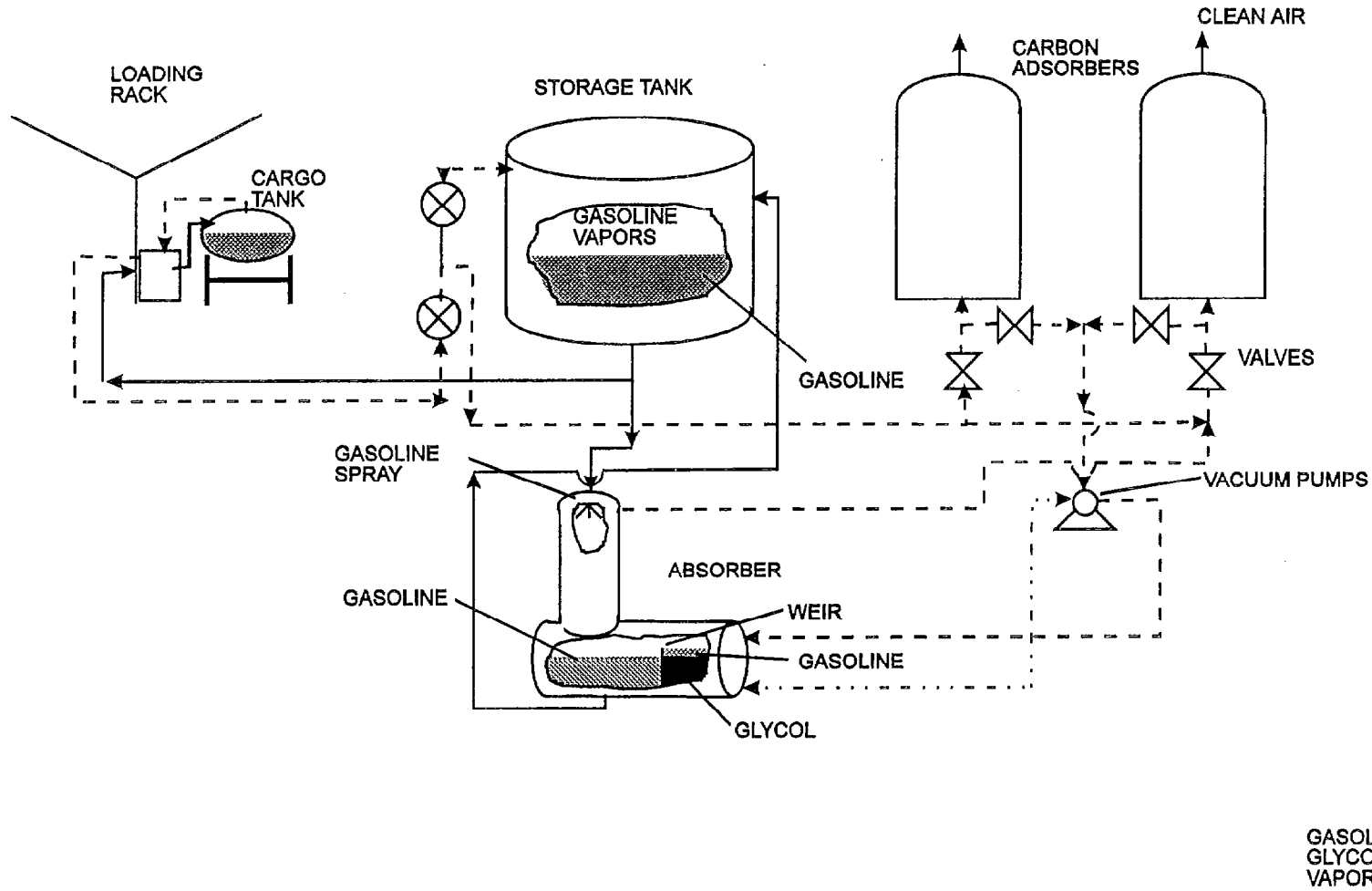


Figure 210.1
Bulk Plant Adsorber and Absorber

200 ADSORPTION

A part of the end of the regeneration step includes allowing ambient air to be pulled into the adsorber when a vacuum is on it. This "polishes off" the carbon bed, removing more gasoline vapors from the bed.

211 ADSORBER SYSTEM WITH STEAM REGENERATION

Figure 211.1 illustrates an adsorber using steam regeneration. A fan provides the energy necessary to move solvent laden air from the process through the adsorption system. The waste stream may flow through a heat exchanger to reduce the temperature of the stream, and a filter to prevent particles from getting into the carbon and reducing its adsorption capacity.

Adsorption continues in one adsorber until its capacity is nearly exhausted. Valves on the line leading to the adsorber close after valves leading to the fresh bed are opened, the exhausted bed is taken off-line and the fresh bed performs adsorption.

Valves on the downstream side of the exhausted adsorber open and inject steam counter-current to the waste stream. The steam desorbs the compounds on the bed by raising its temperature, and forces the compounds out of the adsorber with the steam's high velocity.

Condenser and Decanter

The steam contains the VOCs and goes through a condenser, which is a heat exchanger that lowers the temperature of the steam, condensing it into water. In the decanter, water and the organic compounds are separated from each other. Recovered organic compounds may be reused but the water must be treated before disposal. Ambient air is then put through the adsorber to provide cooling and drying. The bed will then be ready for adsorption again.

212 CALCULATIONS

The instantaneous removal efficiency at any time "t" is the difference between the inlet and outlet concentration divided by the inlet concentration.

η_{it} = Instantaneous removal efficiency at time t

C_{it} = Inlet concentration at time t

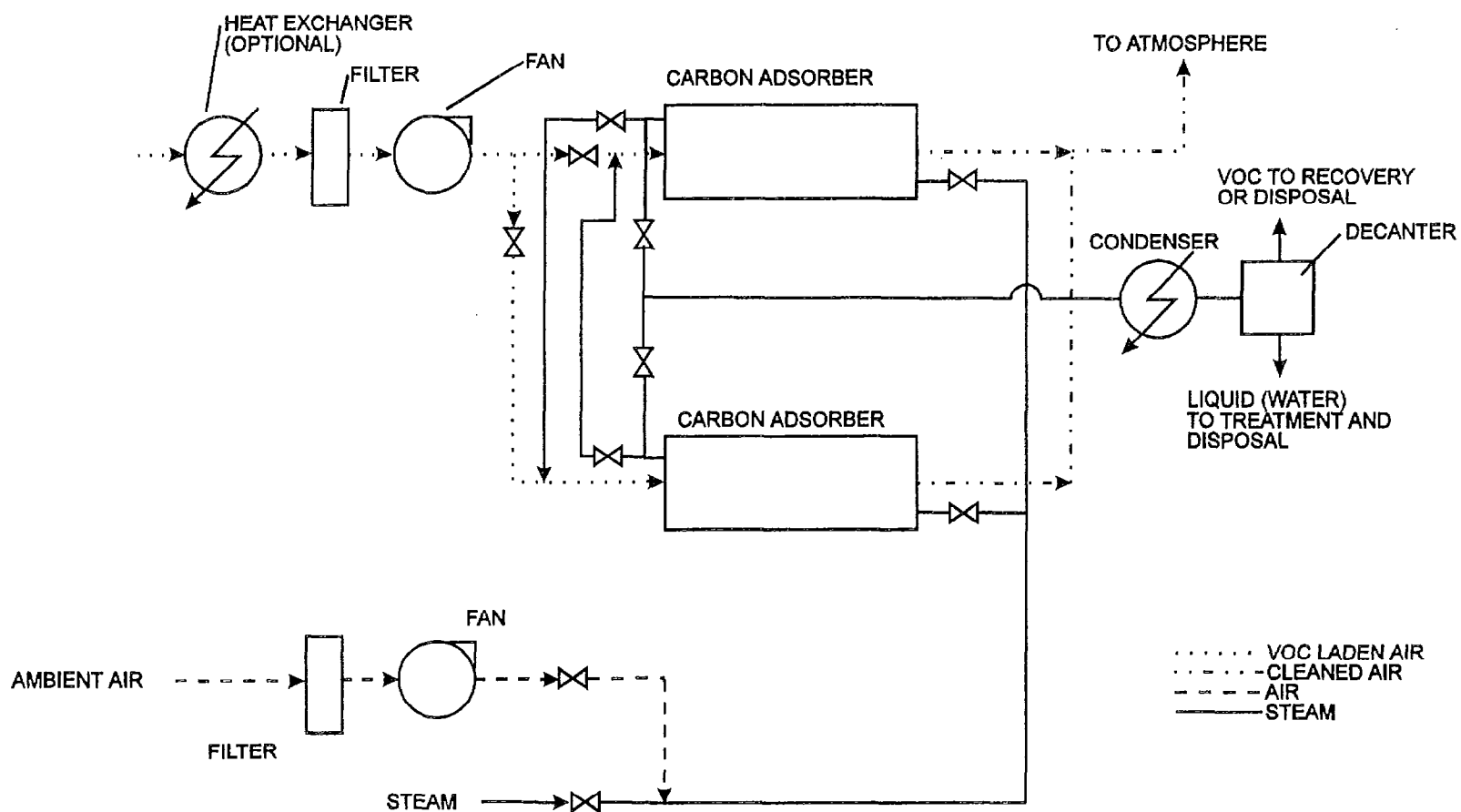


Figure 211.1 Main Components of Carbon Adsorber Using Steam Regeneration

Concentration
Calculation

Co_t = Outlet concentration at time t

$$\eta_{ir_t} = ((Ci_t - Co_t) / Ci_t) 100$$

The calculation of instantaneous removal efficiency at time $t = 1$ is illustrated in Figure 212.1. (Note that C_{sp} is the set point concentration; the point where the adsorber is taken off-line)

The overall efficiency of an adsorber at any time can also be calculated by calculating the average concentration occurring over that time. If the concentrations change during the time the calculation is desired, areas or an integration can be used to calculate the concentration using the outlet and inlet concentration curves.⁶

η_{or_t} = Overall removal efficiency at time t

Ax_t = Area bounded by points A, D, E, and F (A and E are at time $t = 0$; D and F are at time $t = 1$)

Ay_t = Area bounded by points B, C, E, and F (B and E are at time $t = 0$; C and F are at time $t = 1$)

$$\eta_{or_t} = ((Ax_t - Ay_t) / Ax_t) 100$$

212.1 EXAMPLE CALCULATION

If the inlet concentration to an adsorber is 3000 ppmv and the outlet concentration is 150 ppmv halfway through the adsorption period, what is the instantaneous efficiency?

$$\eta_{ir_{1/2}} = ((3000 - 150) \text{ ppm} / 3000 \text{ ppm}) (100) = 95\%$$

If the inlet concentration to an adsorber is 3000 ppmv, what must be the outlet concentration for 99% instantaneous capture efficiency?

$$99\% / 100 = (3000 - Co_t) / 3000$$

$$Co_t = 30 \text{ ppmv}$$

200 ADSORPTION

VOC Control
Devices/
Scrubbers

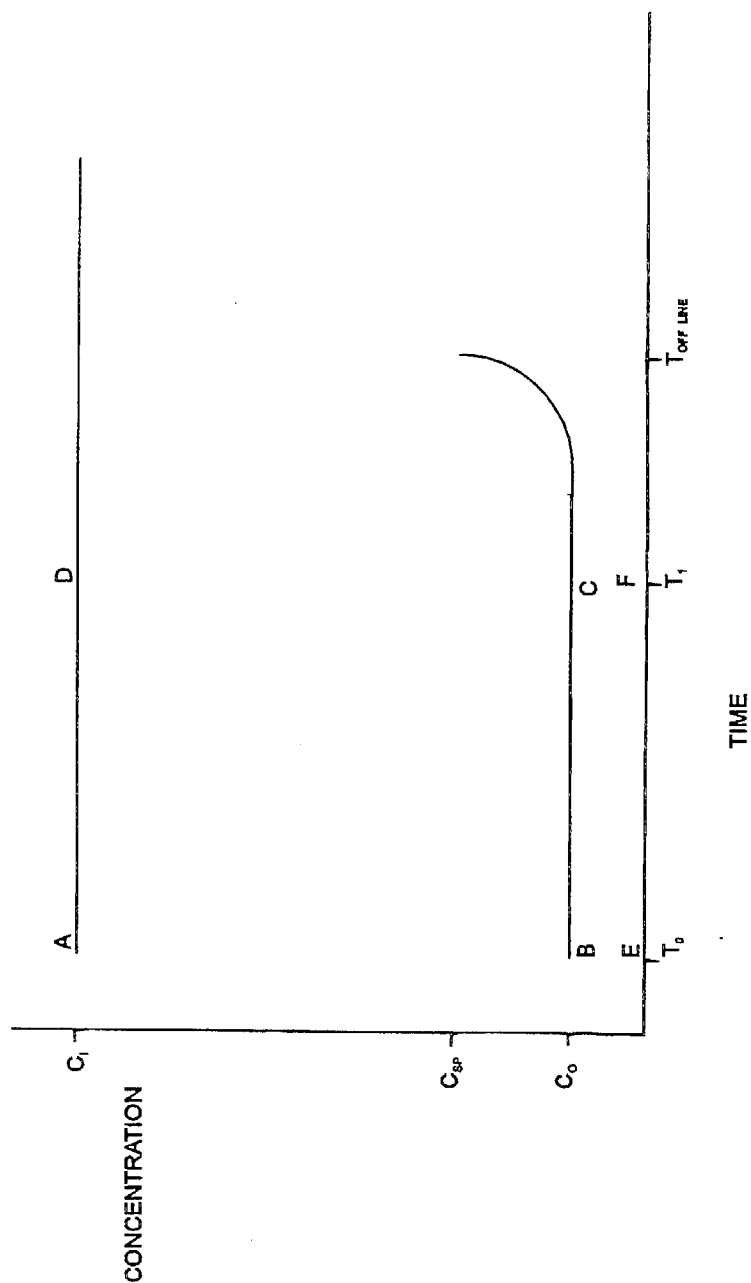


Figure 212.1 Calculating Adsorption Efficiency

200 ADSORPTION

213 RULE DISCUSSION

Local districts - air pollution control districts (APCDs) and multi-county air quality management districts (AQMDs) - have the primary authority and responsibility for enforcing air pollution regulations for stationary sources. Districts regulate with their **rules** and by issuing **Permits to Operate** to companies owning or operating pollution generating equipment. Permits give conditions that companies must comply with in order to legally operate their equipment. Districts can also enforce the federal EPA rules. Many of the district regulations are similar to the EPA's, but in some cases district regulations are more stringent than the EPA's. District rules cannot be less stringent than the EPA's.

213.1 DISTRICT REGULATIONS

Volatile Organic Compounds

District regulations for the control of VOC emissions are primarily made specific to the type of process. Some rules dealing with VOC emissions have requirements for the control efficiency of control devices (also called abatement devices). These control devices include carbon adsorbers. Regulations typically limit the efficiency by mass of VOCs. Typical control efficiencies in district rules include 85, 90, and 95%.

Some rules, such as those with printing and coating operations, give the maximum allowable amount of grams of VOC per liter (g/l) or pounds of VOC per gallon (lbs./gal) in ink, paint or other material. Low VOC products, which are made to comply with these rules, may not work for all applications or may be expensive. Regulations often allow a product with a higher VOC content in excess of rules to be used legally if it is used with a control device (such as a carbon adsorber).

Rules for bulk plants or bulk terminals typically have emission limits in terms of pounds of VOC per 1,000 gallons of organic liquid (i.e. gasoline).

Source tests must be done to determine if the control efficiency of a carbon adsorber or emissions from an adsorber comply with the rules or Permits. Samples of coatings, inks, resins, etc. must be taken to determine if the VOC concentration complies with the rules or Permits.

200 ADSORPTION

VOC Control Devices/ Scrubbers

The kinds of district rules that often have control efficiency requirements or emission limits for control devices include:

- Storage of organic liquids
- Wastewater treatment units
- Bulk plant and bulk terminal operations
- Coil coating operations
- Solvent cleaning/degreasing
- Dry cleaning operations
- Surface coating of metal parts and plastic parts
- Graphic arts operations
- Rubber tire manufacturing
- Pharmaceutical operations
- Magnet wire coating operations
- Pressure relief valves at petroleum refineries
- Aerospace operations
- Semiconductor manufacturing
- Polyester resin manufacturing
- Diskette manufacturing
- Vegetable oil manufacturing
- Paper, fabric and film coating operations
- Wood products coatings
- Automotive coating operations

VOC RECLAIM

RECLAIM (Regional Clean Air Incentives Market) is a regulation that was established by the South Coast Air Quality Management District (SCAQMD). RECLAIM is basically a stationary source emission trading program where a source is subject to a facility-wide mass emissions limit or "cap." Sources in the RECLAIM program are given emission allocations based on their material use and past emission history.

The SCAQMD began developing the RECLAIM program in 1991 for the control of nitrogen oxide and sulfur oxide emissions (NO_x and SO_x). The RECLAIM program officially became effective on January 1, 1994. Large

200 ADSORPTION

sources of NO_x and SO_x have been the only sources subject to RECLAIM. In general, sources must be under the emissions cap given to them by the district, and they must reduce their emissions by 5 to 8% per year.

A RECLAIM program for VOCs has also been recently developed by the SCAQMD. A pilot program has already been conducted, but at the time of the printing of this manual, the regulation was still being drafted and small details were still being ironed out.

The advantages of RECLAIM are that it allows facilities flexibility in developing their own plans toward emission reduction goals. A facility could meet emission limits by reducing production, shutting down for a period of time, acquiring emission control equipment, using low VOC solvents, or by buying emission reduction credits from another company.

Unlike the NO_x and SO_x RECLAIM markets, the VOC market will regulate a larger number of facilities that cover many industries. Sources with over 4 tons of VOC emissions per year will be subject to the VOC RECLAIM market in July 1996. Sources between 2 to 4 tons of VOC per year would come into RECLAIM in July 1998.

Odors

Odors can be sources of public nuisances and some volatile organic compounds used in industrial processes are very malodorous. Most districts use the Health and Safety Code Section 41700 to determine public nuisances. It states:

"Except as otherwise provided in section 41705, (agricultural exemptions) no person shall discharge from any source whatsoever such quantities of air contaminants or other material which cause injury, detriment, nuisance, or annoyance to any considerable number of persons or to the public, or which endanger the comfort, repose, health, or safety of any such persons or the public, or which cause, or have a natural tendency to cause, injury or damage to business or property."

The Bay Area Air Quality Management District also has a rule regarding odors (Regulation 7-300). This rule limits the amount of odorous substances discharged in the air by the amount of dilution by odor-free air required and the

200 ADSORPTION

VOC Control
Devices/
Scrubbers

amount of discharge that occurs. The regulation also limits emission concentrations by ppm for dimethylsulfide, ammonia, mercaptans, phenolic compounds, and trimethylamine.

213.2 PERMITS

Under the authority of the California Health and Safety Code, and in order to comply with the California State Implementation Plan and New Source Performance Standards where applicable, the districts issue Permits to Operate which contain conditions for the operation of industrial processes and emission control equipment. The conditions in Permits reflect the requirements of district rules that apply to a source.

Facilities must function within the parameters stated in the Permit to Operate issued by the district. Permits must be posted on the equipment, where applicable, and they must be current. If these conditions are not adhered to, it is a violation.

The equipment to which the Permit applies is listed on the Permit. It is a violation to operate pollution generating or control equipment that is not permitted. It is also a violation to make modifications to permitted equipment without district approval. When new equipment or modifications are required, a district will issue an Authority to Construct to the owner or operator of the equipment.

Whenever a company must make a modification to its equipment or buy new equipment, it should notify its local district immediately. A district can usually accommodate a source even when modifications must be made in a short period of time.

An Authority to Construct will list the equipment to which it applies and it will list conditions similar to those on a Permit to Operate. After the new equipment is modified or constructed, the district may conduct a source test and issue a Permit to Operate.

Some typical conditions stated on a Permit to Operate for an adsorber may include:

200 ADSORPTION

1. Limits on adsorber inlet temperatures.
2. Limits on pressure drop.
3. Emission limits.
4. Recordkeeping requirements.
5. Requirements for continuous emission monitors.
6. Throughput or production limits (i.e. gallons of solvent material (ink, paint, resin etc.) per day, pounds of material per day).
7. Specific conditions such as:
 - All containers containing volatile material must be closed at all times,
 - Doors must be closed to prevent emissions of odorous compounds, and
 - Solvent material balances must be performed, illustrating amount bought and disposed (and therefore the potential emissions).

214 INSPECTION INTRODUCTION

Sources are inspected in order to verify that a company's equipment is designed, installed, and operated in accordance with air pollution regulations and Permits to Operate. There are four ways that the compliance status of a source can be evaluated:

1. Engineering evaluations
2. Inspections
3. Source testing
4. Continuous emission monitoring

Of these, only the first and third provide actual emission data as to the extent of emissions from a facility. Inspections will primarily be the focus of this section, but source testing and continuous emission monitoring shall be briefly discussed.

200 ADSORPTION

VOC Control
Devices/
Scrubbers

Inspections of facilities may be performed for any one of the following reasons:

1. Compliance determination
2. Complaint investigation as a result of excess emissions or equipment malfunction
3. Source plan approval
4. Review or renewal of Permits
5. Special studies

Reasons for
Inspection

Examples of "special studies" would be operating and maintenance evaluations, or updating emission inventories.

Compliance-type inspections only provide preliminary emissions assessments. Source testing is the method of determining compliance with an emission standard. Compliance inspections are usually unannounced so that a facility can be evaluated under normal operating conditions.

For other inspections pertaining to source construction, plan approval, Permits to Operate, or "baseline type" inspections, the plant should be given sufficient advance notice so that qualified plant personnel can be present to provide the drawings, manuals, and process information that may be required. Prior notice should also be given when performing inspections for special studies designed to document operating and maintenance practices, or process and emission data. This will allow the operator time to make readily available information such as raw material usage, production levels, and stack test results.

Regardless of the type of inspection to be conducted, pertinent supporting information should be obtained prior to, during, and following the source evaluation.

One of the best ways a source can stay in compliance with air pollution regulations is through preventative maintenance inspections. Companies that have efficient inspection and maintenance (I&M) programs tend to have fewer breakdowns, require fewer variances, have less down time and can save money. With an efficient I & M program, problems with equipment can be anticipated and surprising catastrophic failures can be reduced. A good I & M program also requires that neat, orderly, consistent records of self-inspections be kept by the company. Local districts can usually assist sources with I & M programs.

I & M

200 ADSORPTION

214.1 SEQUENCE OF INSPECTION

The sequence of an inspection is a question of what order to inspect the equipment in an adsorption system. The two main logical sequences to follow are a co-current and a counter-flow approach, but regardless of the type of sequence chosen, it is usually best to initially inspect the outside of a facility. By inspecting the perimeter of a plant an inspector can see if there are any illegal emissions or odors before the source is aware of an inspector's presence.

214.1.1 Co-Current Approach

The inspection of a facility using a co-current approach is conducting the inspection in the same general direction as the flow of the gas stream. The general sequence would be the process, the capture system, the control device, and the stack. An inspector may want to use this type of approach when he is unfamiliar with some process details and would like to observe them before seeing the adsorber.

214.1.2 Counter-Flow Approach

An inspection with a counter-flow sequence is conducted against the direction of gas flow. An inspection of this type would generally begin at the stack and continue to the control device, capture system and then the process. The advantage of this approach is that an inspector may be able to more quickly identify where an emission problem originates.

214.1.3 Other Approaches

In some instances an inspector may not start at the stack of the process or the beginning or end of a system. If observations of possible illegal emissions were made while outside the facility, an inspector may want to head directly to the source of the emission. If an inspector suspects illegal tampering of the control device equipment, he may head there directly. If an inspection is a strict, unannounced compliance-type, or if an inspector is very familiar with the process and only has a particular item to deal with, the inspection could start and finish in a different manner.

200 ADSORPTION

VOC Control Devices/ Scrubbers

214.2 LEVELS OF INSPECTION

Four different levels of inspection for carbon adsorption systems have been developed by the U.S. EPA. A level 1 inspection consists of an inspection that is the least in-depth and a level 4 inspection is the most in-depth. The levels are inclusive; a level 3 inspection, for example, would also include all the items done in a level 1 and level 2 inspection. Although these levels may not always be strictly adhered to in practice, the levels help organize all the means in which an adsorption system can be inspected.

For adsorbers no level 1 inspection procedures exist. Visible emissions evaluations are a part of level 1 inspections, but it is unlikely that visible emissions would be emitted from an adsorber. However, a survey of the plant boundary could be considered a part of a level 1 inspection. In a level 2 inspection an inspector conducts a walkthrough evaluation of the carbon adsorption system and process equipment. All the data acquired in a level 2 inspection is acquired from on-site gauges. In a level 3 inspection, independent measurements of adsorber operating conditions separate from the existing on-site gauges are conducted. This is usually done when the existing on-site gauges are inadequate. A level 4 inspection is performed by agency supervisors or senior inspectors to acquire baseline data. As with the level 3 inspection, independent monitoring equipment is used for the level 4 inspection. The "baseline" data acquired in past level 4 inspections is used by inspectors to check the operation of the adsorber in the future.

Level 1 Inspection

Level 2 Inspection

Level 3 Inspection

Level 4 Inspection

215 PRE-INSPECTION PROCEDURES

It is important to prepare for the inspection prior to your visit to the facility. Rules and Permits can be very complicated and preparations must be made for a successful inspection. This section is a discussion of some general guidelines on what steps to follow prior to the inspection.

215.1 FILE REVIEW

Prior to the site inspection, the inspector should review all information available in the district source files including: approved Permits, equipment lists, conditions for each Permit, previous inspection reports, Notices of Violation,

200 ADSORPTION

breakdown reports, enforcement actions taken, odor complaints, variance histories, alternative emissions control plans, abatement orders, source tests, and the design of the carbon adsorption system.

Verify that all applicable Permits for the facility are current and valid. Remember to bring a current copy of the Permit(s) with you and bring extra copies for the source in case they have misplaced or lost their copy.

The inspector may wish to complete some portions of the inspection documentation before arriving at the facility, as this will save time during the pre-inspection meeting. If your district has checklists or rule specific forms, use them.

215.2 REGULATION REVIEW

You should review any references to the specific rules which are noted in the source files. In particular be familiar with each standard and exemption in the rules. Discuss regulations that apply to the facility with experienced personnel and review any policies your district may have. Make sure that you receive consistent interpretations on how to apply the requirements of rules. Review the most recent version of your district's regulation in their entirety.

215.3 EQUIPMENT CHECK

Make sure that you have the following equipment available for use during the inspection: vision protection, hearing protection, safety shoes, hard hat, gloves, identification, business cards, pens, wipes, inspection forms, chain of custody forms, sampling cans, can case, labels, and thermometer.

215.4 PRE-ENTRY AND ENTRY

When you arrive at the plant, notice if there are any strong odors. If there are any odors, make sure you document them and plan on finding the sources as soon as possible after entering the facility.

200 ADSORPTION

VOC Control
Devices/
Scrubbers

Request to see the previous contact mentioned in the files. Depending on the facility, it may be the environmental coordinator, supervisor, president, maintenance worker or operator. Always present your business credentials immediately to avoid confusion.

If the source is unfamiliar with your district's authority, be prepared to cite and provide copies of California Health & Safety Code (CHSC) Section 41510: Right of Entry (a copy is available in the Appendix). Know and follow your district's policy if the facility refuses entry.

215.5 PRE-INSPECTION MEETING

Before the inspection begins, the inspector should meet with the source representative to obtain operating information. The inspector should state the purpose of the inspection and identify the equipment which will be inspected. Facility information can be verified during this meeting, including: the facility name and ownership, address complete with city and zip code, contact name, contact title, phone number and area code. Discuss safety procedures and whether or not there have been any odor problems in the past. Request a copy of material safety data sheets (MSDS), and if necessary discuss sampling procedures.

The district's equipment list on the Permit to Operate should be compared to the facility's Permit to Operate. The items should be the same. If they are not, a Notice of Violation may have to be issued. Also, check existing Permit conditions and ask if any other changes have been made to the operation which are not reflected in the Permit.

216 CARBON ADSORPTION SYSTEM INSPECTION

216.1 ADSORBER SHELL AND DUCT SYSTEM

Check the outside of the adsorber for holes and gaps. Note any excessive corrosion, especially if the corrosion goes all the way through the shell.

200 ADSORPTION

For adsorption systems equipped with a fan and duct system, check the ducts for corrosion, holes, and gaps. There should not be any holes or gaps in the ducts and corrosion should not be excessive. In a positive pressure system, holes and gaps are sources of VOC emissions. In a negative pressure system, holes and gaps will cause air infiltration and will reduce the effectiveness of hoods.

216.2 VOC CONTINUOUS EMISSION MONITORS

If the adsorber is equipped with a continuous emission monitor (CEM) on the stack or outlet gas stream, check the reading and see if it complies with the Permit or baseline value. The reading may be taken from a control room or at the location of the monitor.

CEMs for measuring the outlet VOC concentration are sophisticated pieces of equipment and they may require frequent maintenance. Check calibration records and work orders kept since the last inspection to verify that the monitors have continuously been operating properly and maintained in good working order. If the continuous emission monitor has a chart recorder, make a copy of the records or hand transcribe the records taken since the last inspection. Unless an inspector has time, data from chart recorders should be checked for compliance with rules and Permits after the inspection.

216.2.1 Level 3 and 4 Inspections

In a level 3 inspection an inspector would use his own instruments to measure the concentration of VOCs in the outlet stream from the adsorber or stack. This would usually be done for a source test. The instrument must be properly calibrated and intrinsically safe. Intrinsically safe means an instrument is incapable of causing an explosion when used properly. In general, measurement showing a VOC concentration in excess of 500 ppm is an indication of poor performance.

In a level 3 inspection, existing ports or the stack is used as a location to measure the VOC concentration, but in a level 4 inspection, ports must be put into the ductwork with the help of facility personnel.

**Intrinsically
Safe**

200 ADSORPTION

VOC Control Devices/ Scrubbers

216.3 STATIC PRESSURE AND TEMPERATURE

Check the pressure gauges on the adsorber. Compare the values with the Permit to Operate or baseline values. Pressure readings that are lower than normal may mean that the carbon bed has deteriorated and excessive channeling could be occurring. If the pressure is higher than normal, the carbon bed could be partially plugged. Changes in the process conditions can also affect the pressure in the adsorber. Some gauges may be set up to measure pressure drops across the adsorber and other equipment. If applicable, measure the pressure drop across the hood and compare it with established parameters. Check fan currents and revolutions per minute if necessary.

If an adsorber is equipped with a temperature gauge, measure the temperature of the gas stream upstream of the adsorber. Higher than normal temperatures will reduce the capacity of the carbon bed.

In level 3 and 4 inspections an inspector would use his own instruments to measure the pressure and temperature. In a level 4 inspection measurement ports may have to be installed.

216.4 ADSORPTION/DESORPTION CYCLES

Determine the time interval between carbon bed regenerations and compare the time to baseline values. If the time interval is longer than normal, breakthrough may be occurring, especially if the regenerations are run by timers and if the quantity of organic vapor entering the bed remains unchanged. If the regeneration is done with steam, check the steam pressure. If the pressure is lower than the baseline value, the regeneration cycles may not be as effective as necessary.

216.5 SOLVENT USE

Depending on the system, the effectiveness of a carbon adsorber can be evaluated by creating a solvent material "balance" for the whole system over a period of weeks or months. Some of the data necessary to compute a solvent balance includes the amount purchased, changes in the solvent storage tank

VOC Control
Devices/
Scrubbers

200 ADSORPTION

| Table 216.1 CARBON ADSORPTION INSPECTION FORM A | |
|--|--|
| Pre-Inspection: | Field Inspection: |
| Facility name: Unit I.D. number: | Date/time: |
| Permit number: Permit expiration date: | Inspector: Agency: |
| Facility address: | Facility contact person(s)/title(s): |
| Date unit was built or last modified: | |
| Adsorber Shell and Ductwork | |
| Is this a fan and ductwork system ? Does the system have an enclosed adsorber vessel? | Ductwork and shell condition: Any holes in the ductwork or shell? Is the ductwork or shell excessively corroded? Overall ductwork condition: poor, fair, good (circle one) |

200 ADSORPTION

VOC Control
Devices/
Scrubbers

| Table 216.2 CARBON ADSORPTION INSPECTION FORM B | |
|---|---------------------------------------|
| <u>Pre-Inspection:</u> | <u>Field Inspection:</u> |
| Gauges and Monitors | |
| Is the adsorber equipped with continuous emission monitors? | Continuous emission monitor reading: |
| Maximum outlet concentration: | |
| Maximum adsorber temperature: | Adsorber temperature: |
| inlet: outlet: | inlet: outlet: |
| Pressure drop limits: | Pressure drop: |
| Adsorption/regeneration | |
| Is the carbon in the adsorber regenerated? | Adsorber #1 |
| Is the regeneration controlled by timer or by the outlet concentration? | Regeneration time: |
| Type of regeneration: | Adsorption time: |
| steam, vacuum | Idle time: |
| | Other cycle time (purge etc.): |
| | Adsorber #2 |
| | Regeneration time: |
| | Adsorption time: |
| | Idle time: |
| | Other cycle time (purge etc.): |
| Limit for steam pressure: | Steam pressure during regeneration: |
| Limit for vacuum: | Amount of vacuum during regeneration: |

200 ADSORPTION

levels, and solvents leaving the system. Solvent that went into a process that cannot be accounted for in the recovery in an adsorber or from proper disposal methods may be emissions.

217 POST-INSPECTION PROCEDURES

Prior to leaving the facility, the inspector should evaluate the compliance status of the plant and should have obtained all the information necessary to complete inspection forms. Make sure you have acquired all the necessary documents to determine the compliance of the carbon adsorption operation. Problems that need immediate attention should be shown to the source. A more definite inspection report may be available after all data is reviewed and analyzed.

The facility should be informed of the results of the inspection, advised of areas of concern where additional information or investigation is needed, or given a Notice of Violation (NOV) as soon as possible. Be prepared to make your compliance determinations, calculate excess emissions, and issue all necessary violation notices. Be able to document future NOV's which may be pending due to sample results or additional information requests. **All violations should be followed up**, consistent with your district policy, to ensure that the source is brought into compliance. Always update the Permit file with the actions that took place during the inspection.

300 ABSORPTION

VOC Control
Devices/
Scrubbers

301 INTRODUCTION

This section is a discussion on the absorption process. Regulations regarding absorbers and inspection of absorbers are covered in the Scrubber Section. Absorption is also sometimes referred to as scrubbing, but scrubbers, unlike absorbers, can also be designed to primarily remove particulate matter or dust. Some absorption does occur in scrubbers made to control particulate matter.

Absorption is a process where a soluble component of a gas mixture (absorbate) is removed from the gas by dissolving it in a liquid (absorbent). In absorption, a gas can be absorbed by simply being dissolved within a liquid, or it may be chemically reacted with the absorbing liquid. The liquid used to do the absorbing is relatively nonvolatile. Absorption is a commonly used process in the petroleum and petrochemical industry in bubble towers, distillation columns, fractionators, and other equipment. In terms of air pollution control, absorption is removing a pollutant from a gas stream by dissolving it in a liquid. Absorption is commonly used to control sulfur dioxide (SO_2), hydrochloric acid gases (HCl), sulfuric acid gases (H_2SO_4), nitric acid gases (HNO_3), hydrogen sulfide (H_2S) and odorous compounds.

It is important to note the difference between adsorption, which was previously discussed in Section 200, and absorption. Absorption is different from adsorption in that absorption involves collecting a pollutant (a gas or vapor) by passing it from a liquid surface **throughout the liquid phase**. In adsorption, the pollutant collects on a solid surface and **not within the solid phase**. The pollutant may diffuse into the pores of the solid, but not within its chemical structure. Furthermore, absorption involves removing a gas or a vapor by dissolving into a **liquid** while adsorption involves removing a substance by attaching it to a **solid surface**. Sometimes the term "sorption" is used when absorption and adsorption are both occurring or when there is doubt or confusion as to which process is occurring.

There are different ways to avoid the confusion between adsorption and absorption. One way is to remember that carbon is used for adsorption. In the common term "carbon adsorption" one knows that the term "adsorption" is correct because of the "d" in adsorption. In the alphabet, "d" follows "c" just as in the term "carbon adsorption." Therefore, for example, the term "carbon

**Difference
Between
Absorption
and Adsorption**

Sorption

300 ABSORPTION

absorption is incorrect because "c" comes after "b" in the alphabet. In the incorrect term "carbon absorption" the letters "c" and "b" within the respective words are not in the same order as the alphabet.

302 THE ABSORPTION PROCESS

The absorption process works by the diffusion of a compound from a gas into a liquid. In order for diffusion to occur, the gaseous compound (the solute) must be soluble within the liquid (the solvent). If, for example, a system containing two soluble substances such as gaseous hydrochloric acid (HCl) and water were brought together in a container, hydrochloric acid molecules that came in contact with the water would dissolve in it. A net amount of hydrochloric acid would continue to dissolve in the water until equilibrium is reached. The hydrochloric acid molecules would distribute themselves equally throughout the solvent (water) and the air lying above the water. After equilibrium is reached, the mass of hydrochloric acid dissolving into the solution would equal the hydrochloric acid coming out of the solution and into the gaseous phase.

Chemisorption

As with adsorption, there is also another form of absorption called chemical absorption or chemisorption. This process involves a chemical reaction between the liquid absorbent and the pollutant laden gas. The chemisorption process produces products from chemical reactions that are usually irreversible. Some flue gas desulfurization processes (Section 611) and odor control processes use chemical absorption.

302.1 FACTORS PROMOTING ABSORPTION

In order to make absorption work well for air pollution control, the pollutant and the liquid must be soluble, the diffusion rate across the liquid/gas boundary must be adequate, and the contact between the air and water must be maximized.

300 ABSORPTION

VOC Control Devices/ Scrubbers

Gaseous compounds and liquids that are soluble tend to be chemically similar. Water, for example, is good for absorbing many inorganic compounds. Water-based absorbents are usually used to control acid gases. Volatile compounds within a gas stream are absorbed well by high molecular weight oils and mineral oils. Petroleum is used as an absorbent for volatile petroleum vapors.

In order to promote diffusion, a system must be as far from equilibrium as possible. Diffusion occurs during absorption because there is a relatively high concentration of compounds in a gas but a low concentration of pollutants in a liquid. In order for the system to reach equilibrium, compounds in the gas will try to distribute themselves evenly throughout the liquid.

The rate which a pollutant diffuses into a liquid by absorption is heavily dependent on how far the pollutant and the liquid are kept from equilibrium. Once equilibrium is attained the net mass of a pollutant absorbed will be zero.

Absorption can only occur when the pollutant laden gas and a liquid are in contact. Air pollution control devices utilizing the absorption process are designed to maximize the contact between the pollutant and the liquid. Absorbers generally have a higher gas to liquid ratio than scrubbers used for particulate control. Most absorbers have a gas to liquid ratio between 10 to 80 gal/1000 acf, while most scrubbers have a gas to liquid ratio between 4 and 20.

303 ABSORBER DESIGN

The maximization of pollutant-liquid contact and the application of diffusion, mass transfer and equilibrium principles are involved in the design of an absorber. The biggest requirement of an absorber design is to bring the pollutant gas stream and liquid into contact. This is done by providing a large surface area within the absorber. At the same time, the drag in the device must be minimized so the pressure drop will be as low as possible.

In general, the major steps involved in the design of an absorber are:⁵

Liquid selection

The selection of the liquid or solvent for an absorber is very important. First of all, the liquid must be soluble with the pollutant that will be absorbed. The solubility must be high enough so that the rate of absorption will be adequate. The more soluble the pollutant and the liquid are, the less liquid will be required. The liquid must have low volatility, since the liquid will saturate the gas in an absorber, and some of the pollutants could reenter the gas if the liquid evaporated at a high rate. A liquid with a lower viscosity is better because a liquid with a lower viscosity will absorb pollutants faster. Furthermore, lower viscosity liquids have better flooding characteristics and create lower pressure drops and increased heat transfer. It is best that the liquid have a high freezing point. If the liquid in an absorber froze, it could cause major damage to the equipment. Corrosiveness, cost, toxicity, and flammability are also important considerations. Corrosive liquids will reduce the life of the packing; nonflammable liquids are much safer.

Equilibrium evaluation and estimation of operating data.

The rate which the pollutant and the absorbent liquid will reach equilibrium is taken into account in the design. The further the gas and the liquid are kept from equilibrium, the higher the absorption efficiency will be. A mass and energy balance is performed, where the energy balance decides whether the absorption process can be considered as isothermal or adiabatic.

Column materials and size

Typical absorber shell materials include stainless steel or glass and plastic reinforced polyester (GRP). GRP materials are lighter than stainless steel and are very resistant to acid or chemical attack from most substances encountered in absorbers. On the other hand, GRP materials cannot operate with high temperature gas streams like stainless steel. The main disadvantage of using steel is its susceptibility to damage from halogens.

Internal components, such as packing support plates and spray headers, are usually made of thermoplastics, stainless steel or ceramic materials. The common types of thermoplastics used include PVC, CPVC, and polypropylene. Ceramics are not used as often because they are brittle and susceptible to attack from caustic compounds. As with other parts of the design, the material for the absorber depends heavily on economic considerations.

If the column is not specified given the operating conditions (the pollutant being absorbed, the flow rate of the waste stream, etc.), calculations must be carried out to pick the right size absorber shell for the given operation.

Calculations for packed column diameters are usually based on flooding considerations. Calculations for plate column diameters are usually based on the optimum gas velocity or the liquid handling capacity of the plates in an absorber.

Column height and/or the number of plates

For packed columns, the column height is acquired by multiplying the number of transfer units by the height of a transfer unit. These parameters are usually calculated or read from graphs or charts of experimental data from absorber manufacturers. For plate columns, the number of theoretical plates is determined from plots of equilibrium and operating lines. The actual number of plates is calculated by dividing the theoretical number of plates by estimated overall plate efficiency. If the desired plate spacing is also known, the column height can be estimated from the plate spacing.

Pressure drop

For packed columns, the packing type, column operating conditions, and physical properties help to determine the pressure drop through the packing. In plate columns, the pressure drop per plate is obtained and multiplied by the number of plates.

303.1 PACKED COLUMNS

A common type of absorber is a packed column (or packed tower, Fig 303.1). A packed column is a tower filled with a packing material, where the liquid enters the top of the device and the pollutant laden gas enters the bottom. This counter flow arrangement is the most common design. As the pollutant laden gas stream flows up through the absorber, the absorbent liquid is sprayed from the top and flows downward. As the two flows contact each other, pollutants diffuse into the absorbent liquid. The liquid is usually water, and chemicals are often added to it to control the pH, to react with and neutralize pollutants, and to control properties of the absorbent. After the liquid passes through the absorber it is put into a recirculation tank and recirculated back to the absorber again. The recirculation tank is often the point in the system where chemicals

300 ABSORPTION

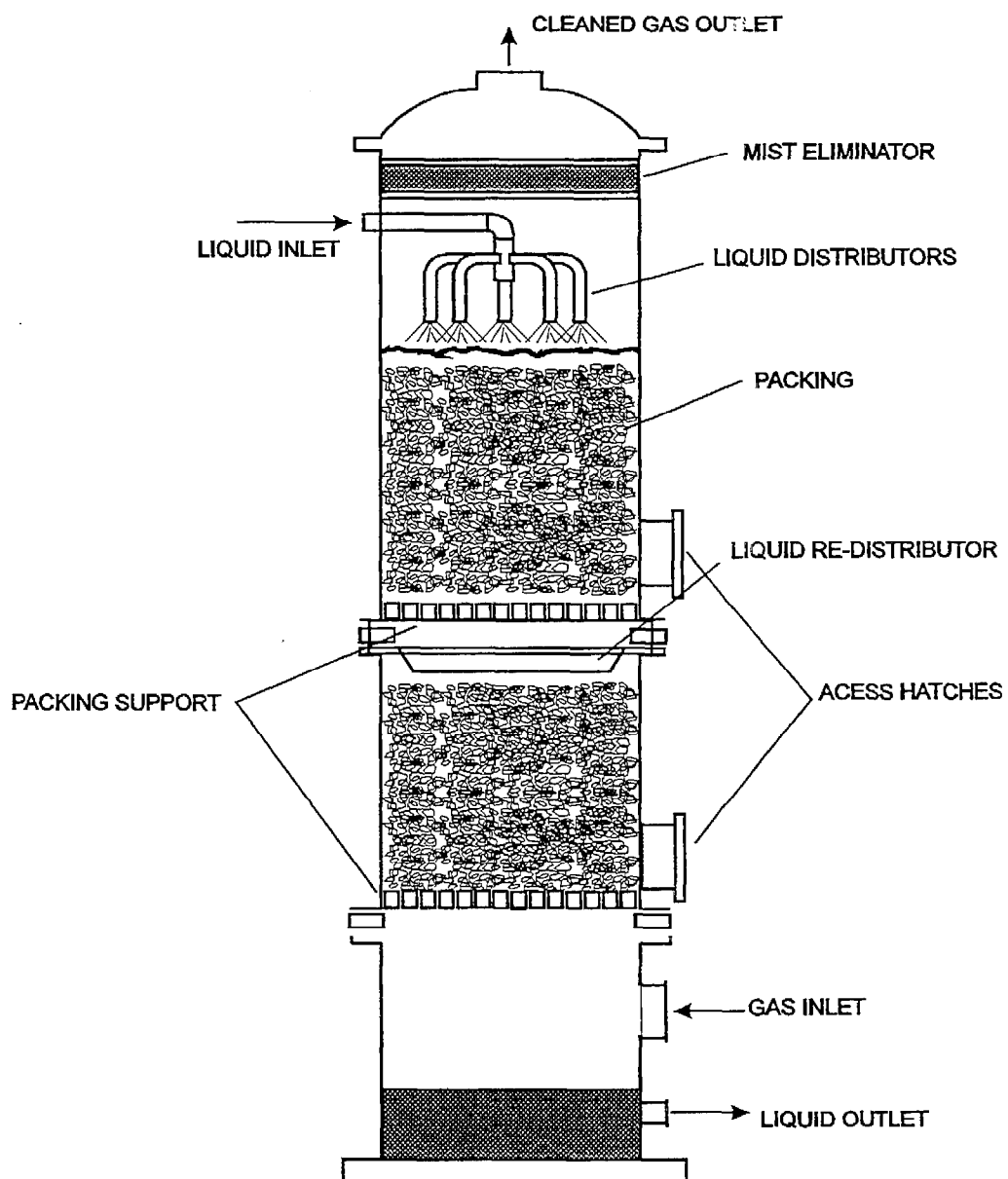


Figure 303.1 Packed Column

300 ABSORPTION

VOC Control
Devices/
Scrubbers

are added. Much less wastewater is created by recirculating the absorbent. Wastewater must be treated before it is discharged to the sewer system. Water in the absorption system is replaced at specified time intervals (i.e. weekly). Systems can also be designed with a constant flow of fresh water.

Packed columns can primarily be used to control the following substances: SO₂ (sulfur dioxide), H₂S (hydrogen sulfide), NH₃ ammonia, CO₂, NO_x, Cl₂, HF (hydrofluoric acid), amines, mercaptans, alcohols, phenols, ethylene oxide, H₂SO₄ (sulfuric acid), acetic acid, formaldehyde, and odors.

Substances
Controlled by
Packed
Columns

A cocurrent flow design, where the liquid and the pollutant laden gas flow in the same direction, can also be used. When a packed tower system is built in two sections, a cocurrent flow system may be employed (Fig. 303.2)⁵. In this system the second tower acts as an economy measure, saving large diameter piping that would be required to connect the two systems. A cocurrent flow design may also be chosen when a system uses a high liquid flow rate, to prevent excessive flooding. Systems with cocurrent flow can handle a higher liquid flow rate than comparable counter flow systems. Cocurrent systems are usually only used when the gases being absorbed are very soluble or when an acidic gas is being absorbed by a caustic liquid.

Absorbers may also operate with a cross-flow design. In a cross-flow packed absorber the liquid and the pollutant laden stream flow perpendicular to each other (see Scrubber Section, Fig. 605.5). As in a counter-flow system, the liquid mainly flows from the top of the device through spray nozzles. Liquid is also sprayed in the horizontal direction on the front face of the packing, in the direction of air flow. Cross-flow systems have a relatively low liquid usage and a relatively high air stream capacity. Cross-flow systems that are used to remove highly soluble pollutants can be better absorbers than counter-flow designs because cross-flow systems have less plugging problems, and fan and motor sizes can be smaller. Cross-flow systems can also use less liquid than counter-flow systems. On the other hand, cross-flow systems suffer from increased liquid entrainment, and more mist elimination is required.

The packing material is an extremely important part of the device. The packing material provides a large "wetted" surface area where pollutants can diffuse into the liquid. Many different types of packings are available (Fig. 303.3).⁵ The main factors that are considered in choosing column packing

Packing

300 ABSORPTION

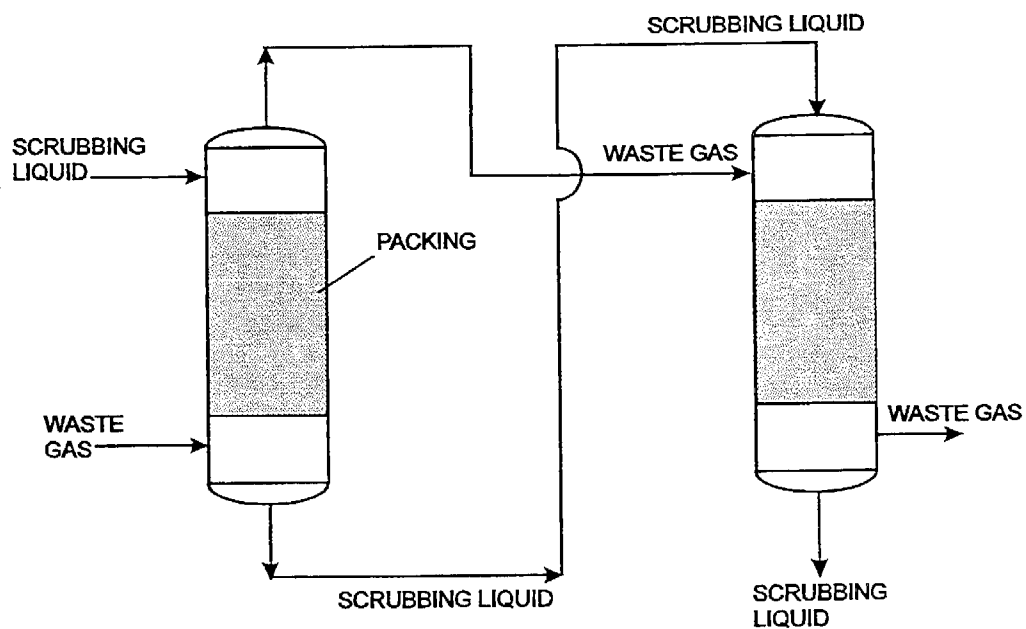


Figure 303.2 Series Counter-current-Co-current Absorption System

300 ABSORPTION

VOC Control Devices/ Scrubbers

include: durability, strength, corrosion resistance, wetted surface area, free space, drag, and cost. Packing must be durable and strong so it will last a long period of time. Strength is important, especially during installation. Some packings can break during installation, so packed columns may be filled with water before the installation. If packings break, the pressure drop across the device may increase. The packing must be resistant to chemical attack; it should especially be immune to acids, since absorption is often used for acid gases. The free space in packing material determines the amount of liquid that will build up in the device. The free space must be right for the flow rate of the liquid. If the liquid buildup is too low, parts of the packing in the column may not be wetted adequately and the efficiency of the pollution control will drop. Each type of packing will have a different surface area. The higher the surface area, the better the pollutants will be absorbed. If the surface area of a packing in a packed column gets too high, the pressure drop may become excessive. Packing is designed to allow air and water flow through with the least drag possible. The higher the drag is, the higher the pressure drop will be.

Packing material can be dumped or randomly stacked in a packed tower during installation or it can be laid out and carefully stacked by hand. Carefully laying out and stacking is time consuming and expensive, but it may provide a flow of air with less drag. Sometimes only the initial layers of packing will be stacked carefully. In general, the normal size of packing should not exceed about 1/20th of the column diameter.⁵

The distribution of the liquid in a packed tower is very important. The liquid at the top of the tower must initially be well distributed. If the liquid is not well distributed, parts of the column may not get wetted and more pollutants could pass through the device without being absorbed. Poor liquid distribution can lead to channeling. A series of spray nozzles are used to distribute the liquid (Fig. 303.1). Channeling happens when portions of the liquid flow only through specific areas. Channeling of the gas stream can also form if the gas stream is poorly distributed.

The design of the liquid distribution system depends on the size of the column, the type of packing, the tendency of the packing to divert liquid to the walls of the column, and the materials of construction for distribution. The liquid in a column with stacked packing has a lower tendency to distribute itself from one side of the column to the other. The liquid moves straight down through the

(Continued on page 300-12)

Liquid Distribution

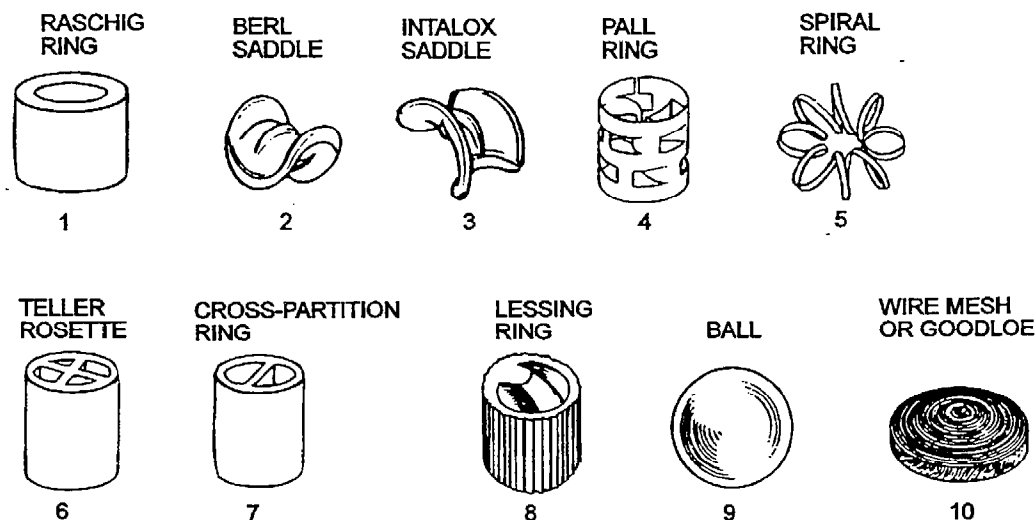


Figure 303.3 Common Absorber and Scrubber Packings

1. Raschig Rings

- One of the most popular types of packing.
- It is a relatively cheap but it is not as efficient for absorption as many other packings.
- Raschig rings are usually dumped, but large Raschig rings (over 4 inch sizes) can be stacked.
- Available in large number of different materials.
- Relatively durable and strong.
- Creates a relatively large thrust force on the sides of the absorption tower.
- Tends to move liquid to the walls of an absorber and is more prone to channeling.

2. Berl Saddles

- More efficient absorption and cost more than Raschig rings.
- Tend to nest together, form areas that are too tight and increase channeling, but occurrence of channeling is less than Raschig rings.
- Thrust force and pressure drop lower than Raschig rings.
- Not as strong as Raschig rings.

3. Intalox Saddles

- One of the most efficient packings for absorption but high in cost.
- Nesting problems are much less than Berl saddles.
- Creates low pressure drop, and has higher flooding limits than Raschig rings.
- Less durable than Raschig rings.

300 ABSORPTION

VOC Control Devices/ Scrubbers

4. Pall Rings

- Has low pressure drop, good liquid distribution, and high flooding limit.
- Creates a relatively large thrust force on the absorber.

5. Spiral Rings

- Relatively large contact surface area.
- Usually stacked when installed.
- Relatively higher pressure drop

6. Teller Rosette

- Lower pressure drop and better flooding characteristics than Raschig rings and Berl Saddles.
- Relatively expensive.
- Light weight/creates relatively small amount of thrust force.

7. Cross-partition Rings

- Relatively low pressure drop.
- Channeling is less than most other similar types of packing.
- Usually installed by stacking by hand so there is no thrust force.

8. Lessing Rings

- Provide absorption somewhat better than Rashig rings but are more expensive and have a higher pressure drop.
- Create relatively high side-wall thrust force.

9. Ceramic Balls

- Create a large contact area for absorption.
- Produce large thrust force.
- Create relatively high pressure drop.

10. Goodloe and Wire Mesh

- Used for distillation, absorption and scrubbing.
- Available in metal only.

Liquid Redistribution

area of the packing it enters. In order to make liquid distribution as uniform as possible and prevent channeling, the liquid must impinge on the bed of packing as uniformly as possible.⁵

After the liquid in the column has fallen some distance through the column, the liquid should be redistributed to prevent channeling. Redistribution may not always be necessary in columns with stacked packing or small columns. Redistributing the liquid brings the liquid off from the sides of the column, where the liquid has a reduced ability to contact the air stream, and directs it toward the center of the device. The distance that a liquid drops before it is recommended to be redistributed depends on the type of packing in the column. When Raschig ring packings are used, for example, the liquid should be redistributed every three column diameters down the length of the column. When saddle packings are used, the recommended redistribution length is five to ten column diameters.⁵ In addition, it is recommended that Raschig rings be used a maximum of 10 to 15 ft per section and saddles be used a maximum of 12 to 20 ft per section. In general, for almost any type of packing, redistribution should be done every 10.0 ft of column length.

Pressure Drop

The pressure drop in a packed column for most packings is a function of the gas flow rate, the liquid flow rate, and chemistry of the system.⁵ The pressure drop for any combination of liquid and gas flows is a very big economic consideration; the larger the pressure drop the higher the cost. If the gas flow rate is held at a constant level, an increase in the liquid flow rate will increase the pressure drop. With an increased liquid flow rate, the liquid takes up more space within the packing in the column. This leaves less space for the pollutant laden gas, restricting the gas flow. If the liquid rate is continually increased, flooding will occur. If the liquid flow rate is held constant and the gas flow rate is increased, the pressure drop will increase. Flooding will also occur if the gas flow rate is continually increased. The operating gas flow rate is usually run at 60% of the gas flow rate that would cause flooding.⁵

Liquid Flow Rate

The major shortcoming of packed towers is that they remove pollutants from a gas stream and put them into a liquid stream; disposal of the liquid waste can be a problem. On the other hand, packed columns are versatile, they have a relatively low pressure drop, they can handle corrosive substances, they have a simple design, and they have relatively low operating costs.

303.2 PLATE COLUMNS

Plate columns, also called bubble-plate columns or bubble towers, are cylindrical vessels that have a series of plates inside to promote absorption. A liquid flows down from the top of the device over the plates while the pollutant laden gas stream flows up through the plates (Fig. 303.4). Each plate has a series of openings designed to permit a pollutant laden gas to bubble through the liquid on top of each plate. The liquid cascades by gravity down from one plate to another through downspouts. As the gas bubbles up through the liquid a froth is formed on top of the plate. The intimate contact between the gas and the liquid allows absorption to occur. Then the same process occurs in the plate above; the gas will again bubble through the liquid on each plate until it reaches the top of the tower. Unlike packed towers, the absorption process in plate columns occurs in a staged process.

303.2.1 Plate Column Design

In order to achieve the highest pollutant collection efficiencies, the contact time between the liquid and the gas stream must be maximized. Keeping the depth of the water on each plate as deep as possible increases the time that the gas and water are in contact. Designing the plates so that the bubbles percolating through the liquid are as small as possible increases the air/liquid contact. Higher gas velocities help increase collection efficiency by increasing froth formation on top of the plates, which helps increase the interfacial surface area.

The depth of the liquid cannot be too deep, because increasing the depth of water on the plates increases the pressure drop across each plate. Higher pressure drops increase the cost of running fans and other equipment. High gas velocities may cause excessive liquid entrainment and a high pressure drop. A plate column design must be a compromise between different factors.

The number of plates inside a plate column depends on the difficulty of separating the pollutant from the gas stream. The diameter of the column depends on the amount of liquid and gas flowing through the tower per unit time. The diameter must be large enough to handle the gas and liquid velocities without causing flooding. Once the number of theoretical plates required is calculated, the number is slightly increased because of plate inefficiencies that cannot be overcome.

300 ABSORPTION

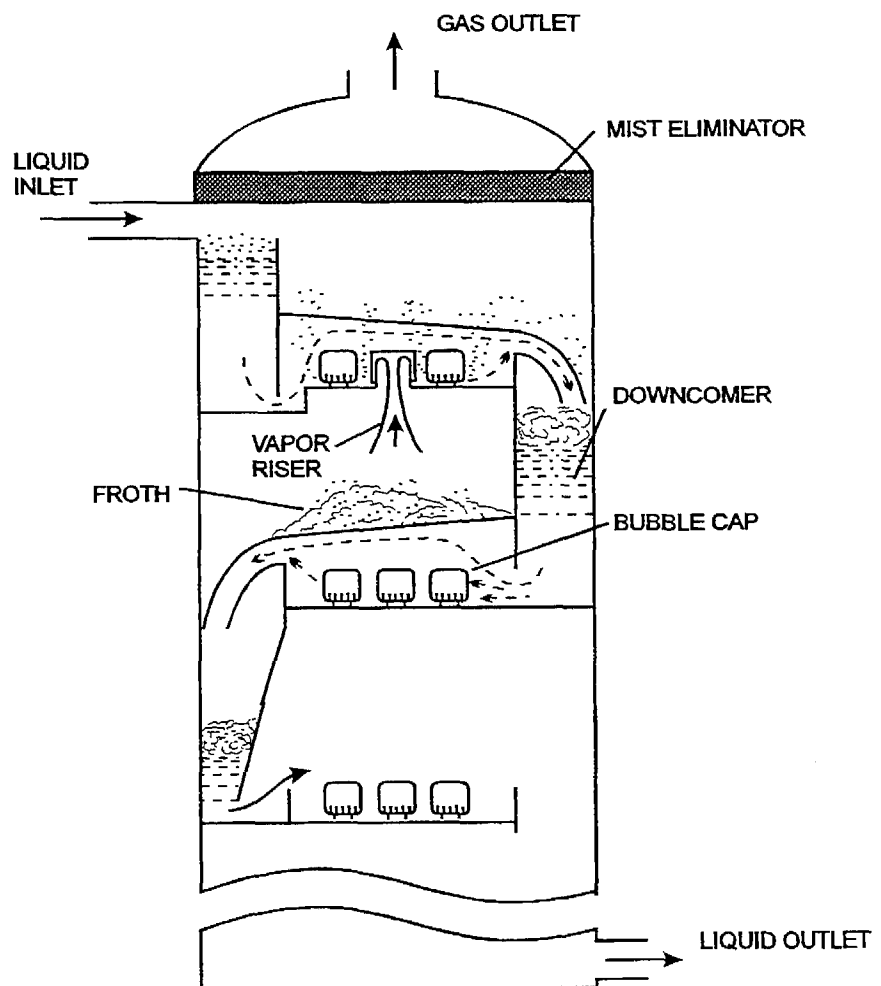


Figure 303.4 Bubble Cap Plate Column

300 ABSORPTION

VOC Control
Devices/
Scrubbers

The design of the plates in a plate column are important in providing a high collection efficiency. Some plates may contain perforations without a downcomer. The holes in perforated plates (also called sieve plates) are usually 0.125 to 1.0 in. in diameter. The holes provide an efficient counter flow system in each hole, allowing for a large degree of contact between the gas and the liquid. Plates using the perforated design without a downcomer are usually spaced 12.0 in. apart. If a downcomer is used with the perforated plate design, the average plate spacing is usually 15.0 in.⁵ Plate designs with a downcomer may also include a weir on the plate for the liquid to flow over. Perforated plate designs are generally not as suitable for designs that operate under variable loads.⁵

Plate Design

Some plate columns have a bubble-cap and riser design to achieve liquid/vapor contact. In a bubble-cap design the gas flows up a tube called a riser, through the plate and into the bubble cap. The bubble cap is a device connected to the riser on the plate that is submerged beneath the liquid on top of the plate. The bubble cap has slots or holes in it to allow the pollutant laden gas to pass into the water as small bubbles. The plates in a bubble-cap plate column are usually 24.0 in. apart. Bubble-cap plate systems are the most flexible plate column design; they can handle high and low liquid and gas rates.

Riser

Bubble Cap

The most important design considerations for plate columns are the calculation of the column diameter, the number of metal plates, the type of metal plates, the plate layout, and the plate spacing. The plate spacing determines the height of the column.

304 PACKED COLUMN CALCULATIONS

After all the flows entering and leaving an absorber have been identified, after the flow rates have been calculated, and after operating conditions have been determined, the dimensions of a packed or plate column can be calculated. A packed column must be tall enough (or long enough, as in cross flow absorbers) to absorb the given pollutant load, and it must have a diameter large enough to accommodate the gas and the liquid.

Stoneware's Pressure Drop Correlation

Calculations for the diameter of a column for an absorber are based on 50 to 75% of the flow rates that cause flooding.⁵ If the gas flow rate and the liquid flow rate of an absorber continually are increased, the flow rates will get so high that the drag on the liquid will be sufficiently high to keep the liquid from flowing freely down the tower. The liquid will accumulate at the tower and will block the entire cross-section from the gas flow. In this condition the pressure drop will increase and the packing will not be able to mix the pollutant laden gas and the liquid.

Stoneware's generalized pressure drop correlation is one of the common plots used to help determine column dimensions. With this plot and a series of calculations, the diameter and the height of a column can be calculated. The following data is used for the calculations: liquid flow rate, gas flow rate at flooding, gas density, packing factor (a coefficient dependent on the packing), and liquid viscosity. See references five and eighteen in Appendix A for the equations and the curves.

The dimensions of the actual column constructed may differ somewhat from the column dimensions that were calculated. Columns are usually constructed from readily available sizes. A lot of money can be saved by ordering sizes that are available. Column diameters within a half foot of the dimensions calculated are usually available; column heights within a foot are usually available.

305 PLATE COLUMN CALCULATIONS

Equation for Gas Velocity at Flooding

For a given plate design, the superficial gas velocity at flooding is:⁵

$$1. V_f = C_f((\rho_l - \rho_g)/\rho_g)^{0.5}$$

V_f = Gas velocity through the net column cross-sectional area for gas flow, $\text{ft}^3/\text{sec-ft}^2$

ρ_l, ρ_g = Density of the liquid and density of the gas respectively (lbm/ft^3)

C_f = An empirical coefficient that depends on the type of plate and operating conditions

For nonfoaming liquids, 80 to 85% of V_f is used in a plate column. For foaming liquids, 75% or less of V_f is used. The pressure drop and entrainment also have an effect on V_f . Since the equation for V_f is based on the gas flow rate, the liquid handling capacity of the system should be checked. If the liquid to gas ratio is high and the column diameter large, the check will indicate

whether the column will show a tendency toward flooding or gas maldistribution on the plate.⁵ If a system shows a tendency toward flooding or gas maldistribution, the liquid rate is the controlling factor in estimating column diameter and an assumption of 30 gal/min for every foot of diameter is made for design purposes. Most well designed systems are actually able to handle up to 60 gal/min for every foot of diameter.⁵

In cases where a relatively dilute gas is used in a plate column, which usually occurs in air pollution control, the number of theoretical plates may be determined through graphical techniques. The number of theoretical plates is usually determined graphically from the operating diagram, composed of an operating diagram and equilibrium curve.

The Kremser-Brown Souders equation can also be used to find the number of plates. (See reference five for more detail on applying equation)

$$2. N_p = \log \left\{ \left[\frac{(Y_{N_p+1} - mX_o)}{(Y_1 - mX_o)} \right] (1 - 1/A) + 1/A \right\} (\log A)^{-1}$$

N_p = Theoretical number of plates

mX_o = The gas composition in equilibrium with the entering liquid (m is Henry's law constant). If the liquid entering a plate column has no solute in it, $X_o = 0$.

Y_{N_p+1} = The solute (pollutant) concentration in the gas stream at the inlet

Y_1 = The solute concentration in the gas stream at the exit.

$$A = L/(mG)$$

L = Liquid flow rate

G = Gas flow rate

$$3. N_{act} = N_p/E_o$$

N_{act} = The actual number of plates

E_o = The overall efficiency of separation

$$4. Z = (N_{act})(h)$$

Z = Tower height

h = The height between plates

In general a plate column is sized by first calculating the theoretical number of stages, using equation #2. Then an estimate of the overall efficiency of separation (E_o) is used to calculate the actual number of plates with

**Kremser-Brown
Souders Equation
for the Number of
Plates**

300 ABSORPTION

equation #3. For h , the height between plates, a value between 12 and 36 in. is used to calculate the tower height (equation #4). Most plate columns have a 24 in. spacing between plates.

306 PACKED COLUMN VS PLATE COLUMN

Although packed columns are used more often in air pollution control, both systems have areas where they are useful. Packed columns should not be used with gas streams that are contaminated with particulates. Particulates may plug up a packed column, but a plate column can handle more particulate matter. Plate columns are better at handling liquids that contain a large amount of sediment. It is easier to remove sediment from plate towers, since they may be fitted with manholes. Cleaning a packed column is more time consuming and costly because it requires the removal of the packing, the cleaning of the vessel and the replacement of the packing.

Packed columns are better at handling air streams containing corrosive substances (acid gases etc.). The packing material can be made of different materials that can be used to resist the pollutant being absorbed by the device. Some plastic and ceramic packings are especially suited for corrosive substances. Plate columns are typically made of steel, which doesn't have as good a corrosion resistance.

If the streams going through an absorber have a large change in temperature, a plate column is usually a better suited control device. Vast temperature changes can do more damage to a packed column, because the packings in the packed column could fail.

Plate columns can operate with a lower liquid rate than packed columns. The liquid rates that could be used for a plate column would flood most packed columns. Plate columns also operate with a higher gas flow rate. The liquids and gases within plate columns are less prone to channeling. Channeling can occur in packed towers if the liquid is not distributed properly. Liquids that have a high tendency to form foam are better suited for packed towers. The foam tendency helps increase the surface area of liquid available for absorption.

300 ABSORPTION

VOC Control
Devices/
Scrubbers

Plate columns are better for absorption processes that involve a chemical reaction. Plate columns have a longer residence time, which allows chemical reactions more time to proceed. On the other hand, with an increased residence time, plate columns operate with a higher pressure drop than packed columns. With a higher pressure drop, the operating costs of moving gas through a packed column will be higher.

Packed columns are more economical for controlling emissions from a smaller system. Small packed columns may only be two to three feet in diameter. Large plate columns tend to be more economical. Packed columns are lighter than plate columns of the same capacity.

400 CONDENSATION

VOC Control
Devices/
Scrubbers

401 INTRODUCTION

Condensation is the process of changing a gaseous substance to a liquid. Condensation can be applied to an air stream contaminated with volatile organic compounds (VOCs) by condensing volatile compounds in a waste stream and removing them. Condensation operations allow valuable solvents to be recovered while providing air pollution control.

Any gas can be condensed into a liquid by reducing its temperature or increasing its pressure. When a gas is cooled the kinetic energy of the gas drops. The random movement of the molecules that make up the gas slows and they stay closer together. Since the molecules are closer together, intermolecular forces (van der Waals forces) can act between the molecules. As mentioned in the adsorption section, van der Waals forces are attractive forces that act between molecules.

Increasing the pressure of a system can cause a gas to condense, because increasing the pressure causes the molecules of a gas to be pushed closer together. This also allows van der Waals forces to act between molecules. Increasing the pressure of a system to promote condensation is rarely done because it is extremely expensive relative to promoting condensation by temperature control. On the other hand, lowering the temperature and increasing the pressure of a system can be done in conjunction to promote condensation.

Therefore, the three ways to promote condensation in a system are to lower the temperature while the pressure is constant, increase the pressure while the temperature is held constant, or decrease the temperature and increase the pressure at the same time.

The conditions under which a gas will condense depend on the physical and chemical properties of the compounds to be condensed. Compounds that have high boiling points (compounds that vaporize at high temperatures) will tend to be easier to condense because the temperature will not have to be lowered as far to promote condensation. A compound in the gaseous state will begin to condense when the partial pressure of that compound equals the vapor pressure of the compound at the same conditions. Furthermore, a compound in a gaseous mixture will also begin to condense if it is cooled to its saturation

Van Der Waals
Forces

Three Ways to
Promote
Condensation

400 CONDENSATION

Partial Pressure

temperature (the saturation temperature for water, for example, at atmospheric pressure (14.7 psi) is 212°F). Reducing the temperature lowers the partial pressure of the gas until it equals the vapor pressure.

The partial pressure of a gas in a mixture of gases is defined as the pressure the gas would exert if it were by itself. This is known as Dalton's law of partial pressures. If, for example, a container contains three gases A, B, and C and if the gases were separated into separate containers, the pressure of the container containing all the gases would equal the summation of the pressure in the separate containers.

$$P_{\text{total}} = P_A + P_B + P_C$$

Condensation works well on many organic compounds because of their relatively high boiling points, even if they are not highly concentrated. On the other hand, as condensation occurs, the partial pressure of the compounds in the gas phase decreases rapidly. Therefore, completely condensing a pollutant from a gaseous stream is not feasible. Toluene, for example has a vapor pressure of 6.0 mm of Hg at 32°F and atmospheric pressure (14.7 psi). If a gas stream was saturated with toluene at these conditions it could still contain a maximum of 8000 ppm at equilibrium.⁵ This is why condensers are not used as much as other control devices such as oxidizers (incinerators) and adsorbers. Condensation is mainly used as a preliminary control device to lower the load on other control devices such as adsorbers, absorbers or incinerators further downstream.

Condensers can be used in a variety of applications for air pollution control in different industries. They are especially useful in the petrochemical industry.

402 EQUIPMENT USED TO CONDENSE POLLUTANTS

402.1 CONTACT AND SURFACE CONDENSERS

The two types of condensers used for air pollution control are contact and surface condensers. In a contact condenser the cooling medium and the product being condensed are mixed together. The medium used to do the cooling is usually water. The volatile compounds condensed in the cooling water may be collected for reuse, or the contaminated water may be treated and

400 CONDENSATION

VOC Control
Devices/
Scrubbers

disposed of. In a surface condenser the volatile compounds and the cooling liquid do not come in contact. The gaseous stream containing volatile compounds and a cooling liquid exchange heat through a solid surface.

402.1.1 Contact Condensers

Contact condensers are generally cheaper to run than surface condensers and are more flexible. Contact condensers are more efficient than surface condensers, are less expensive to install, require less auxiliary equipment, and require less maintenance, but in contact condensers a wet waste stream must be disposed of. Contact condensers usually use water as the coolant that directly contacts the waste stream. Water disposal problems and difficulty in recovering the solvent make the surface condenser the better design in most cases.

The major types of contact condensers include spray condensers, jet condensers and barometric condensers (Fig. 402.1). In the spray condenser, water is sprayed inside the device against the direction of the flow of organic contaminants. In the jet condenser the water and VOC stream meet in an ejector. In the barometric condenser the condensation of vapor in the device creates a negative pressure, pulling vapors into the device.

Types of
Contact
Condensers

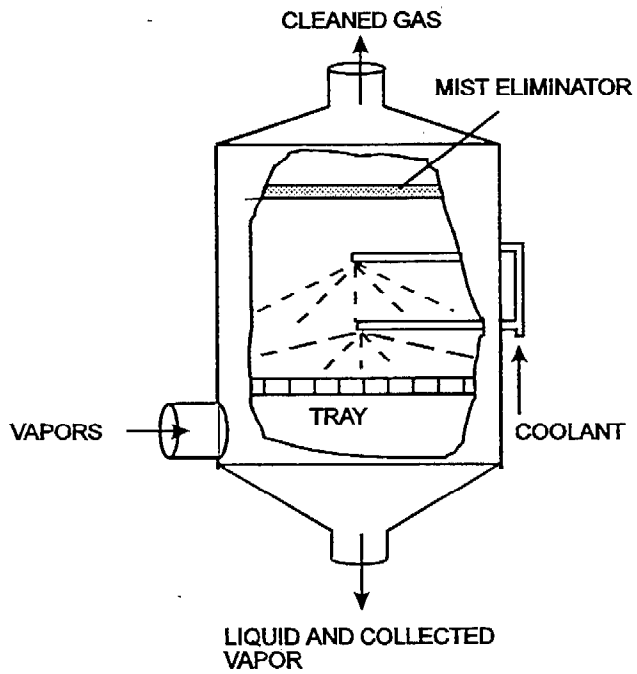
402.1.2 Surface Condensers

Many different designs of surface condensers exist; some of these designs include the shell and tube, fin fan, tubular, double pipe, spiral plate, and flat plate design. The shell and tube design is the most widely used type of surface condenser. Shell and tube condensers are standardized by the Tubular Exchanger Manufacturers Association (TEMA).

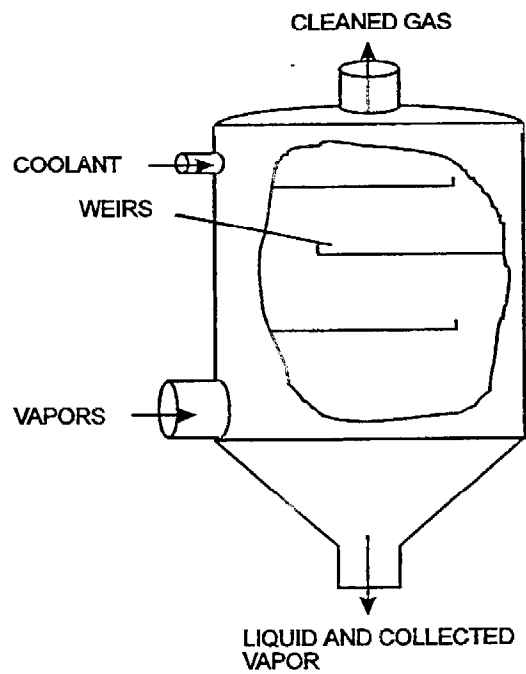
Types of
Surface
Condensers

TEMA

In the shell and tube type of design, a shell encloses a series of tubes (Fig. 402.2). The cooling liquid usually flows inside the tubes and the gas containing volatile compounds usually flows on the outside of the tubes inside the shell. The condenser can also operate with the coolant flowing through the shell and the VOC laden gas stream flowing through the tubes. Surface



SPRAY



BAROMETRIC

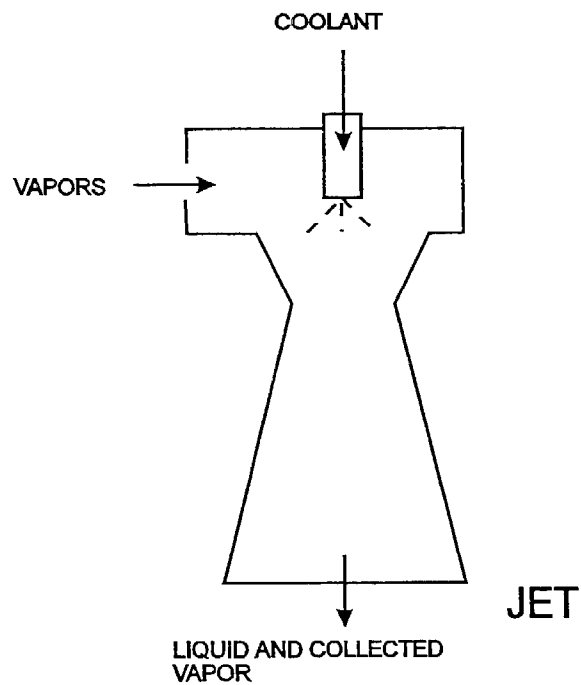


Figure 402.1
Contact Condensers

400 CONDENSATION

VOC Control
Devices/
Scrubbers

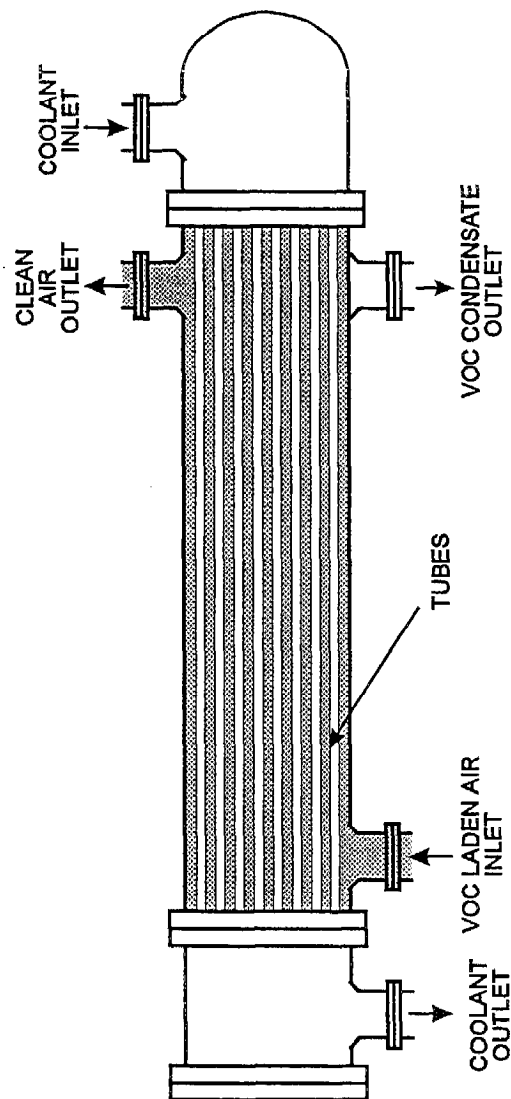


Figure 402.2
Shell and Tube Exchanger (Simplified)

Fin Fans

condensers are also called heat exchangers, since they exchange heat from one stream to another. Surface condensers are usually the kind of condenser used for air pollution control.

Fin fan heat exchangers are air cooled condensers. They have rectangular banks of finned tubes. The fins on the tubes increase the heat transfer between air which flows over the tubes and the VOC laden gas stream flowing through the tubes. The fins are usually made of aluminium, 0.5 to 0.625 inches high, and are welded, soldered, wound to the pipe or cold extruded from the pipe.⁵ Bimetallic tubes can be used to provide corrosion resistance on the insides of the tubes, and aluminum fins help provide corrosion resistance. The device also utilizes large propeller fans which pull air over the tubes and out the top of the unit. Vapors enter the fin fan heat exchanger through ducting, and vapors condensed by the unit are routed away through a condensate line.

Surface condensers can be a single pass, multiple pass, or a cross-flow design. In a single pass condenser or heat exchanger, the cooling fluid and the vapor laden steam are exposed to each other one time. In a multiple pass design the cooling fluid and the vapor are passed by each other more than once. Successive passes are usually used for increased efficiency.

Parallel Flow and Counter- Flow

The flow between the liquid coolant and vapor laden stream can be in parallel flow, if the vapor laden stream and coolant go the same direction, or they can be in counter-flow if the two streams flow in opposite directions. Counter-flow is more efficient, since the temperature gradient between the two streams is essentially constant.² Parallel flow may be used when a fluid is close to freezing, so there will be a larger degree of safety from freezing the condenser. Some condensers, such as a two-pass tube side, single pass shell tubular condenser can have both counter-flow and parallel flow.⁵ Most heat exchangers use a multiple pass design where the two streams, exchanging heat, are routed by each other more than once. This helps improve the efficiency of energy transfer. Another type of design is a cross-flow exchanger, where the cooling liquid and the vapor laden stream flow perpendicular to each other.

The amount that a gas stream can be cooled is dependent on the fluid temperatures in the condenser, the surface area of the tubes, and the ability of heat energy to conduct through the tubes. The colder the cooling fluid is, the more the gas stream temperature can be lowered. When the tubes in a

condenser have more area, there is more contact with the VOC gas stream, allowing for more heat transfer. Therefore, a bigger exchanger will be able to condense more VOCs, but bigger exchangers are much more expensive.

The thinner the tubes are in an exchanger, the better the heat can be transferred from an air stream. Condensers tubes are designed with the thinnest walls possible, and they are made with metal with high thermal conductivities, such as copper. Condensers are also designed with the thinnest tubes possible in order to maximize heat transfer for the least cost. Thin tubes can cause several problems. Condenser tubes may corrode over time and coolant leaks can develop. Tubes can also suffer from erosion. These effects can occur on the inside or the outside of the tubes or in the shell.

The type of coolant chosen is an important consideration for a condenser. The coolant used will primarily depend on the type of plant, and the required efficiency. Some of the common coolants include water from a cooling tower, river, lake, or pond; chilled brine; or a refrigerant.

Condensers can be used in series in a multistage configuration, where one condenser cools the vapor stream and a second condenser cools the vapor stream further. For example, a primary condenser could initially cool the vapor stream and then a condenser using brine could provide additional cooling of the waste stream, condensing out more VOCs.

402.1.3 Fouling and Cleaning

Fouling is a common problem in condensers and heat exchangers. Fouling is the buildup of deposits on the tubes and shells in an exchanger. Fouling can occur on the inside or the outside of the tubes or shells. Fouling reduces the heat exchange effectiveness between the two streams in an exchanger and it increases the pressure drop. Fouling can get so severe that it may plug up parts of a condenser. If severe plugging occurs, fans, pumps, and other equipment can be damaged. If only a few tubes are plugged, they can be replaced or taken out of service by putting metal plugs in them. This is only a temporary measure to keep a condenser operating until it can be taken off line.

400 CONDENSATION

Condensers must be periodically cleaned to remove deposits and prevent the detrimental effects of fouling. The type of deposits determine the type of cleaning method for fouling. Soft deposits can be removed by scrubbing with brushes. Chemical solvents, hot water, and steam may also be used to remove soft deposits.⁵ Caution must be exercised with steam cleaning because it can cause excessive thermal stress.

Mechanical cleaning methods are the best suited for hard-to-remove deposits and they can be used for soft deposits. There are many scrapers, brushes, and cutters available for cleaning tube bundles. Mechanical cleaning techniques require that condensers be opened so that they are accessible to personnel. This makes it necessary to take the equipment out of service.

402.2 REFRIGERATION AND THE PHASEOUT OF CFC

Many condensers use a refrigerant such as freon on the cold side of a surface condenser. The energy to make the process work is provided by a compressor, which is usually run by an electric motor. The compressor makes the refrigerant hot by compressing it; increasing the pressure of a gas adds energy to it and increases its temperature. Heat is then removed from the refrigerant and it is condensed. The refrigerant then expands through an expansion valve and cools; a gas gives up energy when it expands, so its temperature drops. The cold refrigerant then exchanges energy with the VOC laden gas stream through the evaporator coils of the unit, cooling the VOC gas stream and making VOCs condense out of the gas. This part of the unit is called the "evaporator" since it evaporates the refrigerant. Once the refrigerant leaves the coils of the evaporator it goes back into the compressor. It is important that only gaseous refrigerant is in a compressor, since liquids in a compressor can damage the compressor.

A major environmental problem with refrigerants is that many of them are capable of depleting the ozone layer in the upper atmosphere. The ozone layer protects the earth from harmful ultraviolet radiation from the sun. There are many refrigerants available and different refrigerants have different ozone depleting potentials (ODP).

400 CONDENSATION

VOC Control
Devices/
Scrubbers

The most commonly known ozone depleting compounds (ODCs) are fully halogenated chlorofluorocarbons (CFCs), partially halogenated chlorofluorocarbons (HCFCs), bromine-containing halon compounds, methyl chloroform and carbon tetrachloride. Most refrigerants are CFCs or HCFCs. Sometimes refrigerants are generically referred to as "freon." Most refrigerants are simply identified by "R" and a number. For example, R-12, which is also CFC-12, is the refrigerant that is used in most automotive air conditioners.

The ODP (ozone depleting potential) is the estimated steady state ozone depletion per kilogram of emissions relative to the depletion per kilogram of CFC-11. CFC-11 has been given an ODP of 1.0 and all other substances are compared to it in terms of ozone depleting potential. A refrigerant with an ODP of 0.5, for example, would have half the ozone depletion per kilogram from a continuous release as the same release of CFC-11. CFC-12 has an ODP of 1.0; HCFC-22, which is used in many residential air conditioners, has an ODP of 0.05.

One of the early major regulations restricting ozone depleting compounds that led to restrictions affecting condensers was the Montreal Protocol, which was ratified by the U.S. in 1988. Federal regulation for the control of ozone depleting compounds was established by the Clean Air Act Amendments of 1990. The Federal EPA is requiring the phaseout of class I substances, which include halogenated CFCs, halons, carbon tetrachloride, and methyl chloroform, by January 1, 1996. There are some exceptions; methyl chloroform will be phased out completely by 2002. Many of the refrigerants used in condensers will no longer be produced after January 1, 1996.

At the state level, bills have been introduced to control ODCs. AB 691 requires businesses that install mobile air conditioners and have more than two service bays or three or more employees to have certified refrigerant recycling equipment. The Bureau of Automotive Repair is responsible for drafting and enforcing regulations under this bill.

AB 859 banned the sale of 1995 or later motor vehicles using CFC-based mobile air conditioners as of January 1, 1995. Substances with an ODP greater than or equal to 0.1 and covered by the Montreal Protocol are considered to be CFC-based products.

ODP

Refrigerant
Regulations

State
Regulations

Local Regulations

A number of localities also have adopted policies affecting the use and emissions of ODCs. The Bay Area Air Quality Management District and the South Coast Air Quality Management District are two air districts with policies regarding the use of ODCs. Most of the restrictions enacted by localities are very similar to the requirements of the CAAA (Clean Air Act Amendments). Common restrictions in localities include: restrictions on the use and manufacture ODC-containing foam, restrictions on the sale of ODC refrigerant, restrictions on halon use, and recycling requirements for air conditioners and refrigerators.

402.2.1 New Chemical Substitutes

A number of different chemicals are being evaluated by the EPA for being substitutes for ODCs used in different applications. Some of the main considerations for determining if a chemical is an adequate substitute for an ODC include: its thermodynamic properties, the toxicity, the flammability, the costs, the ozone depleting potential, and the global warming potential of the substance.

HFC-134a

The most common chemical substitute for ODCs at the time of the printing of this manual is HFC-134a (also called R-134a) (CH_2FCF_3). In general, it is a good refrigerant for medium temperature refrigeration applications, but not too many low temperature applications. It also works well for some foam blowing applications. HFC-134a is the primary replacement for CFC-12 (R-12) and in some cases HCFC-22. HFC-134a is the new refrigerant for motor vehicle air conditioners.

Some of the disadvantages of HFC-134a are that it is not a refrigerant that is as efficient as CFC-12. On the other hand, the efficiency can be improved by increasing the size of heat exchangers, increasing the size of the compressor, or by improving motor efficiencies. Another problem is that the lubricants used with CFC-12 are not compatible with HFC-134a because they are not soluble in HFC-134a. Mineral-based lubricants were used in CFC-12 systems, but ester-based lubricants which are soluble with HFC-134a can be used with R-134a.

400 CONDENSATION

VOC Control Devices/ Scrubbers

Ammonia is a chemical with excellent thermodynamic properties that works well as a refrigerant, but it is highly flammable and toxic. It has been used as a refrigerant for a long period of time. It is used for refrigeration systems and commercial equipment where exposure to the public is not a problem. It is expensive to change a CFC-based system to one using ammonia, especially when the old system is equipped with copper tubing.

Some other possible substitutes for the near future include HCFC-141b, HCFC-22, HCFC-152a, HCFC-123, HCFC-124 and blends of different combinations of chemicals. The HCFCs generally have lower ODPs than CFCs, but HCFCs will also be phased out by the CAAs by 2030.

402.3 BULK PLANT REFRIGERATION VAPOR RECOVERY SYSTEM

Figure 402.3 illustrates a simplified drawing of a refrigeration vapor recovery system for a bulk plant. In this system a series of refrigeration systems are used to remove heat from the gasoline vapors from gasoline cargo tank trucks loading gasoline.

Each time a truck comes to fill its tanks with gasoline, gasoline vapors within the truck's empty tanks are displaced by liquid gasoline and sent to a vapor holder tank. When the roof of the vapor holder tank rises to a specified level, vapors are sent to the vapor recovery unit.

The vapors first pass over a precooler coil that condenses some of the gasoline into a liquid. The vapor stream is passed over two or three more coils with a much colder temperature to remove more gasoline vapors before the cleaned air that contained vapors is released into the environment.

In Figure 402.3 a precooler compressor compresses CFC-22 (R-22) freon. The R-22 freon is condensed from a gas into a liquid in the condenser. The freon is rapidly expanded, cools, passes through the evaporator coil of a chiller, and exchanges heat with brine (basically a saltwater solution). The chilled brine is pumped into the precooler coil and cools the precooler coil.

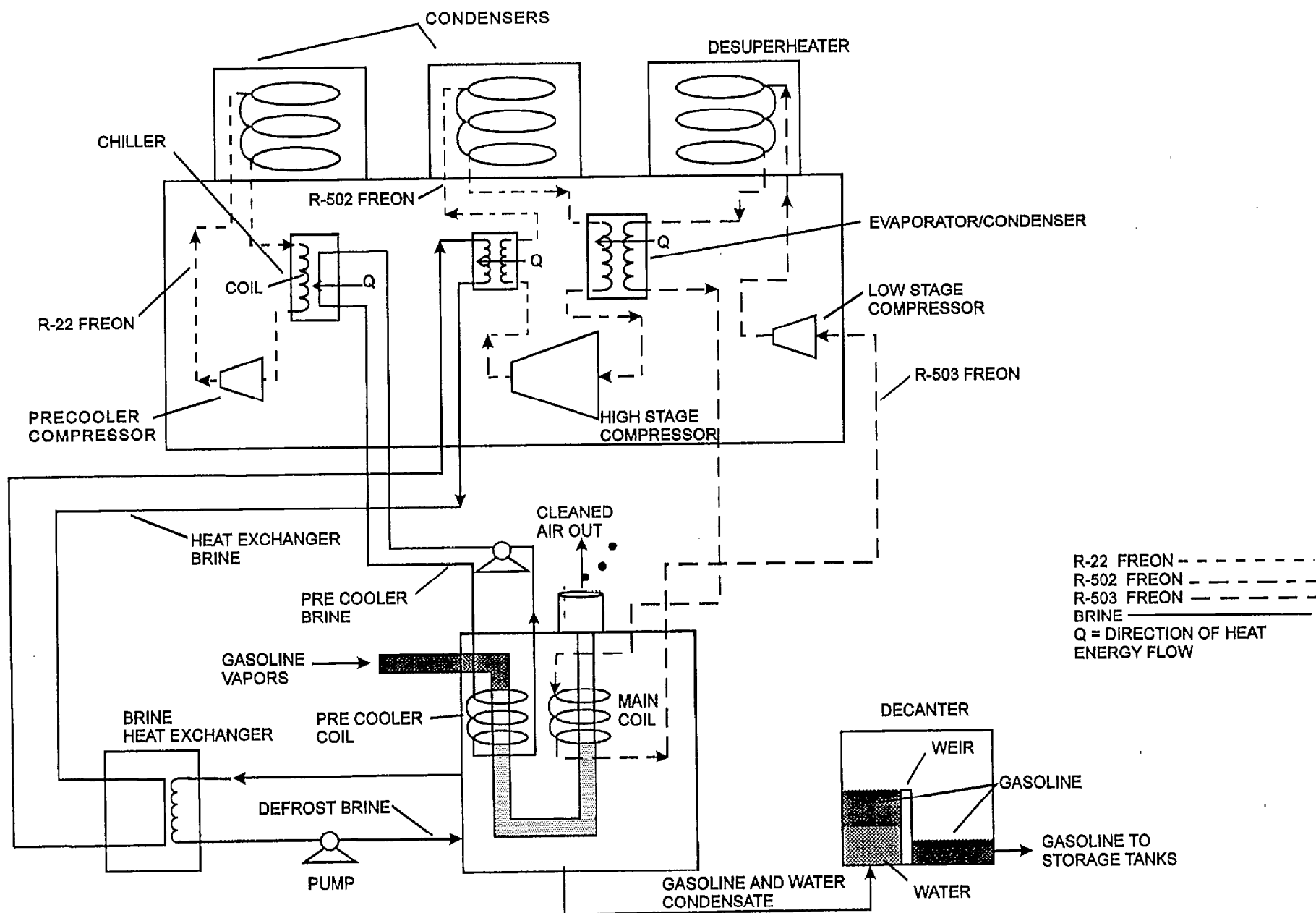


FIGURE 402.3 REFRIGERATION VAPOR RECOVERY SYSTEM

400 CONDENSATION

VOC Control
Devices/
Scrubbers

The next refrigeration system operates with a larger, more powerful, high stage compressor. After the R-502 freon leaves the high stage compressor it is hot, and it is run through a heat exchanger to exchange heat with a brine solution (heat exchanger brine). Hot, heat exchanger brine is run through another heat exchanger where heat is exchanged with another brine solution (defrost brine). The defrost brine is used to remove ice that accumulates on the coils. The gasoline vapor-laden air has water in it just like atmospheric air. The temperature of the coils is below the dewpoint temperature of the air and the main coils are far below the freezing point of water, so water condenses on the coils and freezes.

Cold R-502 freon passes through the evaporator and exchanges heat with cold R-503 freon, making the R-503 much colder than it was from the refrigerator operating on the low stage compressor. The R-503 freon is then passed through the main coil to condense more gasoline vapors.

Gasoline and water condensate are sent to a decanter to be separated. Gasoline is lighter than water, so the gasoline stays on top of the water and flows over a weir. Gasoline is then pumped to storage.

403 BASIC HEAT EXCHANGER RELATIONSHIPS

In order to calculate the heat transfer in heat exchangers, the logarithmic mean temperature difference (LMTD) must be used, because the temperature gradient is not uniform.²

$$LMTD = \Delta T_m$$

ΔT_a = Change in temperature between the hot and cold streams at the left end of the heat exchanger.

ΔT_b = Change in temperature between the hot and cold streams at the right end of the heat exchanger.

$$\Delta T_m = (\Delta T_a - \Delta T_b) / (\ln(\Delta T_a / \Delta T_b))$$

q = Heat exchange (Btu/hr)

U = Overall heat transfer coefficient (Btu/hr-ft²-°F)

A = Area (ft²)

F_c = Correction factor for multiple pass and crossflow heat exchangers

Log-Mean
Temperature
Difference

400 CONDENSATION

Basic Heat Exchange Equation

($F_c = 1$ for single pass exchangers and when one fluid does not change temperature, as when one of the fluid stays saturated)²
If F_c does not equal one, its value can be found from plots in any heat transfer textbook.

Therefore, the heat exchange is:

$$q = F_c UA \Delta T_m$$

Calculating U

U decreases in a condenser as fouling occurs over time. " R_f " is usually used to represent the fouling factor and it has units that are the inverse of U , (i.e. $\text{hr-ft}^2\text{-}^\circ\text{F/Btu}$). U and fouling factors may be acquired from manufacturer information, or from the Tubular Exchange Manufacturer's Association. Some heat transfer textbooks also have tables with fouling factors and have tables with overall heat transfer coefficients with fouling taken into account. Fouling factors can be used to calculate the existing or "dirty" overall heat transfer coefficient in a condenser when the "clean" overall heat transfer coefficient is known. Equations for calculating the existing overall heat transfer coefficient are beyond the scope of this manual, but they can be found in most heat transfer textbooks.

404 PROPER CONDENSER MAINTENANCE

Condensers must be properly maintained in order for the equipment to be in compliance with air pollution regulations and Permits to Operate.

Condenser Problems

There are several conditions that may indicate trouble and/or a poorly maintained condenser. An excessive pressure drop or excessive vibrations may indicate that maintenance is required. If the amount of condensate has decreased or if the outlet temperatures of the vapor laden stream are higher than they were during the last inspection, or higher than they were designed to be, maintenance is required and possible violations could result. Leaking gaskets or connections are also possible violations and require immediate maintenance.

A condenser must be started and shut down properly. Condensers must be slowly and uniformly brought on line to prevent excessive thermal stresses. The bigger the temperature changes will be in the device from the coolant and the vapor stream, the slower the unit must be started. Usually the coolant flow can

400 CONDENSATION

VOC Control Devices/ Scrubbers

be started first and the vapor laden gas stream can then be added gradually. After start-up, connections, bolts, and gaskets should be checked for leaks. Thermal stresses from start-up could slightly mis-align sealing surfaces. Condensers that have fixed tube sheets are more vulnerable to problems due to nonuniform temperature distribution and temperature changes. A condenser should also be taken off-line slowly to reduce thermal stresses. A shutdown is usually accomplished by slowly shutting down the vapor laden gas stream and then the coolant stream. If a condenser will be shut down for a long period of time, the coolant and the vapor laden gas should be removed from the device if any of them contain acidic, alkaline, or corrosive compounds. For safety, flammable materials should also be drained from condensers if they will be shut down for a long period of time.

A condenser must be operated within the limits it was designed to operate. The pressures, temperatures, and flow rate of the device must not be too low or too high. Excessive temperatures could cause excessive thermal stresses, and tubes inside the condenser could fail. If the flow rate is too high, the tubes or parts of the shell could suffer from excessive erosion and leaks could occur in the condenser earlier than expected. Excessive flow rates can also cause vibrations which will lead to damage. Vibrations can also be caused by improper fluid distribution, corrosion, or erosion of internal flow directing devices such as baffles.⁵ Erosion can also occur when flow rates are within established limits. Erosion will occur more rapidly when there are particulates or acidic compounds in the waste stream or in the liquid coolant.

405 RULE DISCUSSION

County air pollution control districts (APCDs) and multi-county air quality management districts (AQMDs) have the primary authority and responsibility for enforcing regulations on stationary sources of air pollution. Districts regulate with their **rules** and by issuing **Permits to Operate** to companies owning or operating pollution generating equipment. Districts can also enforce the federal EPA rules. Many of the district regulations are similar to the EPA's, but in some cases district regulations are more stringent than the EPA's. District rules and regulations cannot be less strict than EPA's.

400 CONDENSATION

405.1 DISTRICT REGULATIONS

Volatile Organic Compounds

District regulations for the control of VOC emissions are primarily made specific to the type of process. Some rules dealing with VOC emissions have requirements for the control efficiency of control devices (also called abatement devices). These control devices can include condensers, but condensers are usually not the control device chosen. Carbon adsorbers or incinerators are usually better options.

Regulations typically limit the control device efficiency by mass of VOCs. Typical control efficiencies in district rules include 85, 90, and 95%. Source tests must be done to determine if the control efficiency of a control device complies with the rule.

Rules for bulk plants or bulk terminals typically have emission limits in terms of pounds of VOC per 1,000 gallons of organic liquid (i.e. gasoline).

The following are the kinds of operations for which district rules often have standards for condensers:

- Solvent cleaning/degreasing
- Dry cleaning operations
- Bulk plant or bulk terminal operations
- Cosmetics manufacturing
- Pharmaceutical operations

The following are the kinds of operations that usually have control efficiency requirements but condensers are usually not the type of control device chosen:

- Storage of organic liquids
- Wastewater separators
- Coil coating operations
- Surface coating of metal parts and plastic parts
- Graphic arts operations
- Rubber tire manufacturing
- Magnet wire coating operations
- Pressure relief valves at petroleum refineries
- Aerospace operations
- Semiconductor manufacturing
- Polyester resin manufacturing

400 CONDENSATION

VOC Control Devices/ Scrubbers

- Diskette manufacturing
- Vegetable oil manufacturing
- Paper, fabric and film coating operations
- Wood products coatings
- Automotive coating operations

Tables 405.1, 405.2, 405.3, and 405.4 illustrate some district regulations that apply to condensers. Do not only rely on these tables to inspect an operation. Refer to district regulations for specific requirements for facilities using condensers.

VOC RECLAIM

RECLAIM (Regional Clean Air Incentives Market) is a regulation that was established by the South Coast Air Quality Management District (SCAQMD). RECLAIM is basically a stationary source emission trading program where a source is subject to a facility-wide mass emissions limit or "cap." Sources in the RECLAIM program are given emission allocations based on their material use and past emission history.

The SCAQMD began developing the RECLAIM program in 1991 for the control of nitrogen oxide and sulfur oxide emissions (NO_x and SO_x). The RECLAIM program officially became effective on January 1, 1994. Large sources of NO_x and SO_x have been the only sources subject to RECLAIM. In general, sources must be under the emissions cap given to them by the district, and they must reduce their emissions by 5 to 8% per year.

A RECLAIM program for VOCs has also been recently developed by the SCAQMD. A pilot program has already been conducted, but at the time of the printing of this manual, the regulation was still being drafted and small details were still being ironed out.

The advantages of RECLAIM are that it allows facilities flexibility in developing their own plans toward emission reduction goals. A facility could meet emission limits by reducing production, shutting down for a period of time, acquiring emission control equipment, using low VOC solvents, or by buying emission reduction credits from another company.

400 CONDENSATION

Table 405.1
Condenser Standards for Perchloroethylene Dry Cleaning Systems

| <u>District</u> | <u>Regulation</u> | <u>Limits</u> |
|-----------------|-------------------|---|
| BAAQMD | 8-27-302.3 | The air temperature at the outlet of a refrigerated condenser must reach 45 degrees F or less during the cool-down period. |
| SCAQMD | 1102.1 c,2 | A temperature gauge with a minimum range of 0 to 150 degrees F must be installed on the condenser outlet duct. |
| BAAQMD | 8-27-302.1 | (or) The control efficiency for any control device must be 90% by weight or greater before discharge of exhaust gases to the atmosphere. |
| SCAQMD | 1102.1 c,3 | |

400 CONDENSATION

VOC Control
Devices/
Scrubbers

Table 405.2
Condenser Limitations for Pharmaceuticals and
Cosmetics Manufacturing Operations

| <u>District</u> | <u>Regulation</u> | <u>Limits</u> | |
|-----------------|-------------------|---|--|
| BAAQMD | 8-24-301 | No reactors, distillation columns, crystallizers, or centrifuges shall emit more than 15 lbs. of VOC per day unless the vents are equipped with surface condensers or equivalent control devices. | |
| SCAQMD | 1103 c,1 | | |
| BAAQMD | 8-24-301.1 | The condenser outlet temperature must be controlled at the following vapor pressures and temperatures as shown below: | |
| SCAQMD | 1103 c,1,A | | |
| | | Absolute vapor pressure at 68 degrees F (20 degrees Celcius): 0.5 psia to 1.0 psia 1.0 psia to 1.5 psia 1.5 psia to 2.9 psia 2.9 psia to 5.8 psia over 5.8 psia | Maximum condenser outlet gas temperature: 77 degrees F (25 deg. C) 50 degrees F (10 deg. C) 32 degrees F (0 deg. C) 5 degrees F (-15 deg. C) -13 degrees F (-25 deg. C) |

400 CONDENSATION

Table 405.3
Condenser Limits for Solvent Cleaning Operations (BAAQMD)

| <u>Regulation</u> | <u>Limits</u> |
|---|---|
| 8-16-301, 1.1 8-16-302, 1.1 8-16-303.1 1.1 | The emission control equipment shall be operated and maintained in proper working order. |
| 8-16-301.4, 4.2 8-16-302.5, 5.2 8-16-303.4, 4.3 | Vapor solvent cleaners, conveyORIZED solvent cleaners, and cold cleaners must be equipped with a freeboard chiller where the chilled air blanket temperature measured in degrees F at the coldest point on the vertical axis in the center of the solvent cleaner is no greater than 30% of the initial boiling point of the solvent or 40 degrees F. |
| 8-16-301.4, 4.3 8-16-302.5, 5.3 8-16-303.4, 4.4 | (or) An approved emission control system with 90% or greater control efficiency on a mass basis. |

400 CONDENSATION

VOC Control
Devices/
Scrubbers

Table 405.4
Condenser Limits for Solvent Degreasers (SCAQMD)

| <u>Regulation</u> | <u>Limits</u> |
|-------------------|---|
| 1122 e,4,A | Open top vapor degreasers, which have an air vapor interface surface area of more than 10.8 ft sq. (1 sq. m.) equipped with a refrigerated freeboard chiller, must have a refrigerant temperature at the degreaser outlet that does not exceed 40 degrees F (4.4 degrees C). |
| 1122 e,6,C | The refrigerated condenser and the freeboard chiller for open top vapor degreasers shall be turned on simultaneously or before the sump heater is turned on. At shutdown, the sump heater shall be turned on either simultaneously or before the condenser water and the refrigerated freeboard chiller are turned off. |
| 1122 f,6 | Conveyorized vapor degreasers which have an air vapor interface surface area of more than 10.8 sq. ft. (1 sq. m) but less than or equal to 21.6 sq. ft. (2.0 sq. m), equipped with a refrigerated freeboard chiller, must have a refrigerant temperature at the degreaser outlet that does not exceed 40 degrees F (4.4 degrees C). |
| 1122 f,7 | Conveyorized degreasers which have an air vapor interface surface area of more than 21.6 sq. ft. (2.0 sq. m), equipped with a refrigerated freeboard chiller, must have a refrigerant temperature at the degreaser outlet that does not exceed -4 degrees F (-20 degrees C). |

400 CONDENSATION

Unlike the NO_x and SO_x RECLAIM markets, the VOC market will regulate a larger number of facilities that cover many industries. Sources with over 4 tons of VOC emissions per year will be subject to the VOC RECLAIM market in July 1996. Sources between 2 to 4 tons of VOC per year would come into RECLAIM in July 1998.

Odors

Odors can be sources of public nuisances. Most districts use the Health and Safety Code Section 41700 to determine public nuisances. It states:

"Except as otherwise provided in Section 41705, (agricultural exemptions) no person shall discharge from any source whatsoever such quantities of air contaminants or other material which cause injury, detriment, nuisance, or annoyance to any considerable number of persons or to the public, or which endanger the comfort, repose, health, or safety of any such persons or the public, or which cause, or have a natural tendency to cause, injury or damage to business or property."

The Bay Area Air Quality Management District also has a rule regarding odorous emissions (Regulation 7-300). This rule limits the amount of odorous substances discharged in the air by the amount of dilution by odor free air required and the amount of discharge that occurs. The regulation also limits emission concentrations by ppm for dimethylsulfide, ammonia, mercaptans, phenolic compounds, and trimethylamine.

405.2 DISTRICT PERMITS TO OPERATE

Under the authority of the California Health and Safety Code, and in order to comply with the California State Implementation Plan and New Source Performance Standards where applicable, the districts issue Permits to Operate which contain conditions for the operation of industrial processes and emission control equipment. The Permit conditions in a Permit to Operate generally reflect the requirements of rules that apply to a source.

400 CONDENSATION

VOC Control Devices/ Scrubbers

Facilities must function within the parameter stated in the Permit to Operate issued by the district. Permits must be posted on the equipment, where applicable, and they must be current. If these conditions are not adhered to, it is a violation.

Permits have an equipment list listing the equipment that applies to it. It is a violation to operate pollution generating or control equipment that is not Permitted. It is also a violation to make modifications to Permitted equipment without district approval. When new equipment or modifications are required, a district will issue an Authority to Construct to the owner or operator of the equipment.

Whenever a company must make a modification to its equipment or buy new equipment, it should notify its local district immediately. A district can usually accommodate a source even when modifications must be made in a short period of time.

An Authority to Construct will list the equipment to which it applies and it will list conditions similar to those on a Permit to Operate. After the new equipment is modified or constructed the district may conduct a source test and issue a Permit to Operate.

Some typical conditions stated on a Permit to Operate on an operation using a condenser include:

1. Limits on maximum outlet temperature in the condenser.
2. Limits on pressure drop.
3. Recordkeeping requirements.
4. Throughput limits (gallons of gasoline delivered, amount of material produced or used).
5. Requirements for continuous emission monitors.
6. Specific conditions regarding the process:
 - Using complying solvents
 - Keeping lids on solvent containers

Modifications

ATCs

400 CONDENSATION

- Keeping solvent material balances
- Disposing of waste in enclosed containers etc.

406 INSPECTION INTRODUCTION

Sources are inspected in order to verify that a company's equipment is designed, installed, and operating in accordance with air pollution regulations and Permits to Operate. There are four ways that the compliance status of a source can be evaluated:

1. Engineering evaluations
2. Inspections
3. Source testing
4. Continuous emission monitoring

Of these, only the first and third provide actual emission data measurements from a facility. Inspections will primarily be the focus of this section, but source testing and continuous emission monitoring shall be briefly discussed.

One of the best ways a source can stay in compliance with air pollution regulations is through preventative maintenance inspections. Companies that have efficient inspection and maintenance (I&M) programs tend to have fewer breakdowns, require fewer variances, have less down time and can save money. With an efficient I & M program, problems with equipment can be anticipated and surprising catastrophic failures can be reduced. A good I & M program also requires that neat, orderly, consistent records of self-inspections be kept by the company. Refrigeration vapor recovery systems like the one discussed earlier, typically require a lot of regular maintenance for continuous, efficient operation. Local districts can usually assist sources with I & M programs.

Reasons for Inspections

Inspections of facilities may be performed for any one of the following reasons:

1. Compliance determination
2. Complaint investigation as a result of excess emissions or equipment malfunction
3. Source plan approval

400 CONDENSATION

VOC Control Devices/ Scrubbers

4. Review or renewal of Permits
5. Special studies

Examples of special studies would be operating and maintenance evaluations, or updating emission inventories.

Compliance-type inspections only provide preliminary emissions assessments. Source testing is the method of determining compliance with an emission standard. Compliance inspections are usually unannounced so that a facility can be evaluated under normal operating conditions.

For other inspections pertaining to source construction, plan approval, Permits to Operate, or "baseline type" inspections, the plant should be given sufficient advance notice so that qualified plant personnel can be present to provide the drawings, manuals, and process information that may be required. Prior notice should also be given when performing inspections for special studies designed to document operating and maintenance practices, or process and emission data. This will allow the operator time to make readily available information such as raw material rates, production levels, and stack test results. Regardless of the type of inspection to be conducted, pertinent supporting information should be obtained prior to, during, and following the source evaluation.

406.1 SEQUENCE OF INSPECTION

The sequence of an inspection is a question of what order to inspect the equipment in a system. The two main logical sequences to follow are a co-current and a counter-flow approach, but regardless of the type of sequence chosen, it is usually best to initially inspect the outside of a facility. By inspecting the perimeter of a plant an inspector can see if there are any illegal emissions or odors before the source is aware of an inspector's presence.

406.1.1 Co-Current Approach

The inspection of a facility using a co-current approach is conducting the inspection in the same general direction as the flow of the gas stream. The general sequence would be the process, the capture system, the control device,

400 CONDENSATION

and the stack. An inspector may want to use this type of approach when he is unfamiliar with some process details and would like to observe them before seeing the condenser.

406.1.2 Counter-Flow Approach

An inspection with a counter-flow sequence is conducted against the direction of gas flow. An inspection of this type would generally begin at the stack and continue to the control device, capture system and then the process. The advantage of this approach is that an inspector may be able to more quickly identify where an emission problem originates from.

406.1.3 Other Approaches

In some instances an inspector may not start with the stack of the process or the beginning or end of a system. If odors were detected outside the facility, an inspector may want to head directly to the source of the odor. If an inspector suspects illegal tampering with the control device equipment he may head there directly. If an inspection is a strict, unannounced compliance-type, or if an inspector is very familiar with the process and only has a particular item to deal with, the inspection could start and finish in a different manner.

406.2 LEVELS OF INSPECTION

Four different levels of inspection have been developed by the U.S. EPA. These levels are classified as 1, 2, 3, or 4, where a level 1 inspection consists of an inspection that is the least in-depth and a level 4 inspection is the most in-depth. The levels are inclusive; a level 3 inspection, for example, would also include all the items done in a level 1 and level 2 inspection. Although these levels may not always be strictly adhered to in practice, the levels help organize all the means in which a system can be inspected.

Visible emissions evaluations are a part of level 1 inspections, but it is unlikely that visible emissions would be emitted from a condenser. However, a survey of the plant boundary could be considered a part of a level 1 inspection. In a level 2 inspection an inspector conducts a walkthrough evaluation of the

400 CONDENSATION

VOC Control
Devices/
Scrubbers

condenser system and process equipment. All the data acquired in a level 2 inspection is acquired from on-site gauges. In a level 3 inspection, independent measurements of operating conditions separate from the existing on-site gauges are conducted. This is usually done when the existing on-site gauges are inadequate. A level 4 inspection is performed by agency supervisors or senior inspectors to acquire baseline data. As with the level 3 inspection, independent monitoring equipment is used for the level 4 inspection. The "baseline" data acquired in past level 4 inspections is used by inspectors to check the operation of the condenser and process equipment.

407 PRE-INSPECTION PROCEDURES

It is important to prepare for the inspection prior to your visit to the facility. Rules and Permits can be very complicated and preparations must be made for a successful inspection. This section is a discussion of some general guidelines on what steps to follow prior to the inspection.

407.1 FILE REVIEW

Prior to the site inspection, the inspector should review all information available in the district source files including: approved Permits, equipment lists, conditions for each Permit, previous inspection reports, Notices of Violation, breakdown reports, enforcement actions taken, odor complaints, variance histories, alternative emissions control plans, abatement orders, source tests, and the design of the condenser system.

Verify that all applicable Permits for the facility are current and valid. Bring a current copy of the Permit(s) and bring extra copies in case the facility has misplaced or lost their copy.

The inspector may wish to complete some portions of the inspection documentation before arriving at the facility, as this will save time during the pre-inspection meeting. If your district has checklists or rule specific forms, use them.

400 CONDENSATION

407.2 REGULATION REVIEW

You should review any references to the specific rules which are noted in the source files. In particular, be familiar with each standard and exemption in the rules. Discuss regulations that apply to the facility with experienced personnel and review any policies your district may have. Make sure that you receive consistent interpretations on how to apply the requirements of rules. Review the most recent version of your district's regulation in its entirety.

407.3 EQUIPMENT CHECK

Make sure that you have the following equipment available for use during the inspection: vision protection, hearing protection, safety shoes, hard hat, gloves, identification, business cards, pens, wipes, inspection forms, chain of custody forms, sampling cans, can case, labels, and thermometer.

407.4 PRE-ENTRY AND ENTRY

When you arrive at the plant, notice if there are any strong odors. If there are any odors, make sure you document them and plan on finding the sources as soon as possible after entering the facility.

Request to see the previous contact mentioned in the files. Depending on the facility, it may be the environmental coordinator, supervisor, president, maintenance worker or operator. Always present your business credentials immediately to avoid confusion.

If the source is unfamiliar with your district's authority, be prepared to cite and provide copies of California Health & Safety Code (CHSC) Section 41510: Right of Entry (a copy is available in the Appendix). Know and follow your district's policy if the facility refuses entry.

400 CONDENSATION

VOC Control
Devices/
Scrubbers

407.5 PRE-INSPECTION MEETING

Before the inspection begins, the inspector should meet with the source representative to obtain operating information. The inspector should state the purpose of the inspection and identify the equipment which will be inspected. Facility information can be verified during this meeting, including: the facility name and ownership, address complete with city and zip code, contact name, contact title, phone number and area code. Discuss safety procedures and whether or not there have been any odor problems in the past. Request a copy of material safety data sheets (MSDS), and if necessary discuss sampling procedures.

The district's equipment list on the Permit to Operate should be compared to the facility's Permit to Operate. The items should be the same. If they are not, a Notice of Violation may have to be issued. Also, check existing Permit conditions and ask if any other changes have been made to the operation which are not reflected in the Permit.

408 CONDENSER SYSTEM INSPECTION

408.1 OVERALL CONDENSER CONDITION

Check the condition of the outside of the condenser shell, ductwork, and pipes. Note any corrosion or rust. Small amounts of corrosion or discoloration are normal, but the corrosion should not be so serious that it compromises the structural integrity of the unit. If serious corrosion is discovered, check for holes in the unit and ductwork.

Look for coolant leaks. In contact condensers, leaking liquids could be sources of VOC emissions. If the condenser is a negative pressure system, where the fan is downstream of the control device, check for air infiltration. Also, check for leaks in the ductwork or piping carrying the solvent laden waste stream. Look for any holes in the ductwork or gaps in the joints. Holes and gaps can be sources of VOC emissions.

Beware of unusual noises or excessive vibrations. This could mean the fan or compressor has a serious problem. For safety, an inspector should leave the area if excessively vibrating equipment is discovered.

400 CONDENSATION

408.2 CONDENSER TEMPERATURE

Locate the temperature gauges for the condenser; they may be directly on the unit or in the control room. The outlet temperature is an important indicator of condenser performance. The temperature must be kept low enough so VOCs will be continually removed efficiently. Compare the temperature reading with the Permit to Operate or baseline value. Make sure the temperature gauge appears to be working before recording the reading. The outlet temperature must be within the range on the Permit or it is a violation. If the condenser has a chart recorder for the temperature, acquire a copy of the temperature records. The records will indicate if the outlet temperature of the condenser has been exceeded since the last inspection.

408.3 PRESSURE DROP

The condenser may also be equipped with a pressure gauge. If the condenser has a pressure gauge, see if it appears to be working properly and record the reading. Compare the reading with the Permit or baseline value. Pressure drops that are higher than normal may indicate that the unit is partially plugged.

408.4 CONTINUOUS EMISSION MONITOR

If the condenser is equipped with a continuous emission monitor, record the emissions. Acquire a copy of the chart recorder records. The records will indicate if there have been exceedances of the maximum emissions limits on the Permit to Operate. If applicable, acquire a copy of the calibration records for the continuous emission monitor.

If possible, go to the stack or vent where the cleaned air is released into the environment. See if there are any detectable solvent-like odors.

400 CONDENSATION

VOC Control
Devices/
Scrubbers

**Table 408.1
CONDENSER INSPECTION FORM**

| <u>Pre-Inspection:</u> | <u>Field Inspection:</u> |
|---|--|
| Facility name: Unit I.D. number: | Date/time: |
| Permit number: Permit expiration date: | Inspector: Agency: |
| Facility address: | Facility contact person(s)/title(s): |
| Date unit was built or last modified: | |
| Condenser Design and Condition | |
| Condenser type: contact condenser, surface condenser Coolant type: Type of contact condenser design: spray, jet, barometric | Any excessively corroded or rusted equipment? Any leaking coolant or VOC? Any excessive odors? |
| Gauges and Monitors | |
| Is the condenser equipped with a continuous emission monitor? | VOC outlet concentration: Waste stream flow rate: |
| Maximum outlet concentration: | Condenser outlet temperature: |
| | Condenser pressure drop: |
| | Coolant pressure: Coolant flow rate: |

400 CONDENSATION

408.5 LIQUID FLOW RATE

If the condenser is equipped with a gauge indicating flow rate, record the reading and check it with the Permit or baseline value. This will indicate if the condenser is being fed enough liquid. Spray nozzles on contact condensers can get plugged and reduce the flow. Severe fouling in a surface condenser may also affect the liquid flow rate. If a pressure gauge is on the condenser for the liquid flow, verify it is within proper limits.

408.6 SOLVENT RECOVERY/DISPOSAL SYSTEM

Check the integrity of any pipes that handle the condensed solvent. Check for any excessive corrosion on the disposal or recovery system. Any holes or gaps could be sources of VOC emissions.

If the recovered solvent or volatile organic compounds are recovered or reused, make sure they are sent to an enclosed tank or an enclosed system that does not leak. If the condensed solvents are disposed of, make sure they are put into enclosed containers or destroyed, and there is no way for the compounds to escape into the atmosphere.

For contact condensers, make sure the decanter or separation system for removing the volatile compounds from the liquid is totally enclosed. Check that the liquid and volatile compounds are disposed of properly.

408.7 REFRIGERATION SYSTEM

If possible, check the coolant level of the condenser and makes sure it is not too high or too low. Check the integrity of the coolant supply and return lines.

409 POST-INSPECTION PROCEDURES

Prior to leaving the facility, the inspector should evaluate the compliance status of the plant and should have obtained all the information necessary to complete inspection forms.

400 CONDENSATION

VOC Control
Devices/
Scrubbers

The facility should be informed of the results of the inspection, advised of areas of concern where additional information or investigation is needed, or given a Notice of Violation (NOV) as soon as possible. Be prepared to make your compliance determinations, calculate excess emissions, and issue all necessary violation notices. Be able to document future NOV's which may be pending due to sample results or additional information requests. **All violations should be followed up**, consistent with your district policy, to ensure that the source is brought into compliance. Always update the Permit file to reflect actions that took place during and as a result of the inspection.

500 INCINERATION

VOC Control Devices/ Scrubbers

This section deals with the destruction of volatile organic compounds (VOCs) by combustion. For further information on incineration and solid waste incineration, please see the Incineration Technical Manual from the Air Resources Board Compliance Assistance Program.

The terms "incinerator," "oxidizer," and "afterburner" are often used interchangeably to mean the same thing. On the other hand, "incinerator" can mean a solid, liquid, or gaseous waste incinerator. Furthermore, an afterburner is a control device for controlling gases from a combustion process that was not complete. In this section "incinerator" describes the control device for gaseous emissions (primarily VOCs). The term "oxidizer" will also be used in this section.

501 COMBUSTION BASICS

Incinerators for the destruction of VOCs from processes are often used when it is not economical to recover solvents. Combustion involves destroying VOCs by reacting them at a rapid rate with oxygen.

The combustion process releases heat; it is an exothermic process. The rate at which combustion occurs is highly dependent on the temperature of the system. Some compounds are so volatile that oxygen will combine with them at room temperature. For example, a pile of solvent or paint-soaked rags can be a fire hazard. The hydrocarbons slowly oxidize, releasing small amounts of heat which raises the temperature of the rags. The speed of the reaction then increases and the rags may catch on fire and begin to burn rapidly. This process initially may take hours, but once the slow oxidation has raised the temperature enough, the rags burn rapidly.

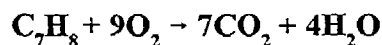
In order for combustion to occur, the ignition temperature of any air/fuel mixture must be reached. Furthermore, in order to maintain a flame, a mixture of air and combustibles must provide enough heat to maintain the combustion temperature. The energy contained in a mixture of air and most organic materials at the lower flammable limit is, generally, equivalent to approximately 52 Btu/scf. Therefore, at ambient temperature the organic vapors and liquids in the air must provide at least 52 Btu/scf (Btu/standard cubic foot) to initiate a

500 INCINERATION

Hydrocarbons

flame by a high temperature source and keep it sustained.³ Once a system undergoing combustion generates more heat than it loses to its surroundings, additional energy to support combustion will not be required. In an incinerator, high temperatures are necessary to get complete combustion between oxygen and VOCs traveling through the incinerator at a rapid rate.

Compounds of hydrogen and carbon atoms are called hydrocarbons; carbon containing compounds are also known as organic compounds. Many VOCs are primarily made of carbon and hydrogen atoms. When most VOCs are burned, carbon dioxide and water are usually the main compounds formed. If the solvent toluene (C_7H_8) is burned with oxygen, the following reaction occurs:



Although carbon dioxide is a greenhouse gas, it is not considered to be a pollutant and the water is also considered to be nonpolluting. This is why combustion is a clean method to control many VOCs.

When some compounds are burned, new pollutants that are worse than the original compounds being burned can be created. When a waste gas contains sulfur or chlorinated compounds, undesirable substances such as hydrochloric acid, sulfur dioxide, and hydrofluoric acid can be created in the exhaust. Additional controls may then be necessary on an oxidizing system to control these emissions.

Atmospheric Air

There are several problems that arise using combustion control devices. First of all, atmospheric air instead of oxygen is used to react with compounds. Atmospheric air is composed of 78% nitrogen, 20.9% oxygen, and a 1% total of carbon dioxide, water vapor, argon, helium and a very small percent of other inert gases. For most combustion applications, all the atmospheric components are grouped with nitrogen, making air composed of approximately 20.9% oxygen (O_2) and 79.1% nitrogen (N_2). In terms of mass, the atmosphere is approximately 76.85% nitrogen and 23.15% oxygen.

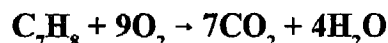
If the temperature of combustion gets high enough, the nitrogen in the air will react, forming NOx compounds. The amount of NOx formed also depends on the type of fuel. When diesel fuel is burned, for example, NOx is one of the

500 INCINERATION

VOC Control Devices/ Scrubbers

main pollutant emissions formed. Most of the NO_x compounds formed from combustion are nitrogen oxide (NO), but nitrogen oxide can later photochemically react to form nitrogen dioxide (NO₂), a major pollutant.

Another problem that occurs with combustion is incomplete combustion. Incomplete combustion occurs when there are not enough oxygen molecules to react with the fuel (the solvent or VOC). When incomplete combustion occurs, carbon monoxide (CO), unburned hydrocarbons, aldehydes, organic acids and other compounds can be produced. Carbon monoxide is a pollutant and hydrocarbons can photochemically react to form ozone (O₃). Incomplete combustion can be avoided by using excess air. In the chemical reaction for toluene, nine oxygen molecules are required to react with one molecule of toluene for complete combustion.



This is called Stoichiometric combustion. The chemical reaction also illustrates from the coefficients in front of each compound that one molecule (or one mole) of toluene will combust completely with nine molecules (or nine moles) of oxygen. Therefore, 1 ft³ of toluene requires 9 ft³ of oxygen to burn completely. Excess oxygen is required because all of the fuel otherwise cannot find oxygen molecules to react with during combustion. The amount of excess air usually varies from 5 to 200%. The amount of excess air that can be used in a combustion system is limited. Excess air has to be heated up to the combustion temperature. When more excess air is used, more fuel is required to heat the excess air, increasing fuel costs. Therefore, the least amount of excess air possible is used to get adequate combustion. Adding excess air maximizes the amount of carbon dioxide (CO₂) produced. An air/fuel mixture that has too much air is called a **lean** mixture. An air/fuel mixture that has too much fuel and not enough air is a **rich** mixture.

In order to make complete combustion, adequate **temperature**, **turbulence**, and **time** are required. These three items are known as the three T's of combustion. Any of the three T's can be modified to attain the required combustion efficiency. As illustrated earlier, the temperature must be high enough to ignite an organic waste and fuel. Turbulence (or mixing) is required to mix oxygen molecules with fuels and organic wastes. Oxygen molecules need time to come in contact with all the fuel and organic waste molecules in order for complete combustion to occur.

Incomplete Combustion

Stoichiometric Combustion

Lean and Rich

Three T's of Combustion

500 INCINERATION

Residence Time

In the real world, complete 100% efficient combustion is not attained. Improper mixing can create incomplete combustion. Getting appropriate mixing in an incinerator is one of the most difficult things to design for the device. Obstructions in a combustion chamber can create turbulence but they must be carefully designed. Dead spots, which reduce temperature and destruction efficiency, can be created in combustion chambers by obstructions. Refractory baffles, swirl-fired burners or baffle plates are used to mix air and fuel more efficiently in an incinerator. Mixing can also be excessive in an incinerator. Excessive mixing can quench the flame.

Although combustion is a chemical reaction that occurs at an extremely rapid rate, time is required for the chemical reaction to occur. The amount of time that wastes have in an incinerator to burn is called the residence time. Residence time can be increased by designing a larger chamber for combustion. When the combustion chamber is longer, it takes more time for the hot, burning gases inside to exit the incinerator. This increases VOC destruction. Temperature, turbulence and time are dependent on each other. If the temperature is raised, a lower residence time will result at the same rate and efficiency of combustion and vice-versa.

502 INCINERATION SYSTEMS

Combustion devices used to control VOCs include thermal incinerators, catalytic incinerators, boilers, process heaters, and flares. The three main incineration techniques used by these devices include a direct flame, high temperatures (thermal oxidation), and catalytic oxidation. Flares use a direct flame to oxidize waste gases. Thermal incinerators, boilers and process heaters use high temperatures from combustion to oxidize pollutants. Catalytic incinerators use elevated temperatures (lower than thermal incinerators) with a catalyst to provide oxidation.

A number of different factors help determine the type of combustion equipment required. The type of organic compounds and their concentration, the process flow rate and economic considerations help determine the most appropriate device.

500 INCINERATION

VOC Control
Devices/
Scrubbers

Thermal incinerators and catalytic incinerators can handle up to 100,000 scfm of waste gas. Both systems can obtain up to 98% destruction efficiency of VOCs.⁸ Since the volatile compounds destroyed in incinerators are often flammable, for safety considerations VOC concentrations within an incinerator are limited to 25% of the lower explosive limit (L.E.L.) of the VOC. If the concentration is higher than 25% of the lower explosive limit, the VOC may be diluted with air. Table 502.1 shows the concentration of common compounds corresponding to 25% of the L.E.L.

Lower
Explosive Limit

502.1 THERMAL INCINERATORS

In a thermal incinerator (also called thermal oxidizers or afterburners) waste gases are passed through a combustion chamber where VOCs are destroyed. Figure 502.1 illustrates a thermal incinerator with a horizontal burner. The major parts of the device include the burner, refractory lined combustion chamber (combustor), and exhaust stack. The burner is typically equipped with a flashback arrestor, combustion air supply controller, and fuel rate controller. The flash back arrestor prevents the equipment from catching on fire. The air supply controller and fuel rate controller control the air and fuel rate respectively to attain the proper air/fuel ratio for efficient combustion. A thermocouple is often used on the burner to help maintain the proper air/fuel ratio.

Incinerators controlling VOCs raise the temperature of the VOC-containing waste stream entering the incinerator to a sufficiently high temperature to oxidize the compounds. The burner must continually operate since the VOC waste stream is not rich enough to support combustion.

Thermal incinerators use a burner flame to heat the relatively cool gas stream several hundred degrees Fahrenheit above the autoignition point of the VOCs being oxidized. The range of autoignition of most VOCs is between 800 and 1400°F. Natural gas is the most common fuel used to provide the heat energy for the incinerator.

The temperature in the combustor is kept high relative to other combustion control devices, between 1300 to 2370°F (700 and 1300°C) to assure high chemical reaction rates and efficient VOC destruction. In order to keep the

Thermal
Incinerator
Temperature

500 INCINERATION

Table 502.1
Concentration for 25% of LEL for Common Compounds

| Compound | Concentration (ppm) |
|---------------------|---------------------|
| Acetaldehyde | 10,000 |
| Acetone | 7,500 |
| Acrolein | 7,000 |
| Benzene | 3,500 |
| Butane | 4,750 |
| Cellosolve acetate | 4,250 |
| Cyclohexanone | 2,750 |
| Ethane | 7,500 |
| Ethylene | 7,750 |
| Furfural | 5,250 |
| Isopropyl alcohol | 5,000 |
| Methyl acetate | 7,750 |
| Methyl alcohol | 18,250 |
| Methyl ethyl ketone | 4,500 |
| Propylene | 6,000 |
| Styrene | 2,750 |
| Toluene | 3,500 |
| Xylene | 2,500 |

500 INCINERATION

VOC Control
Devices/
Scrubbers

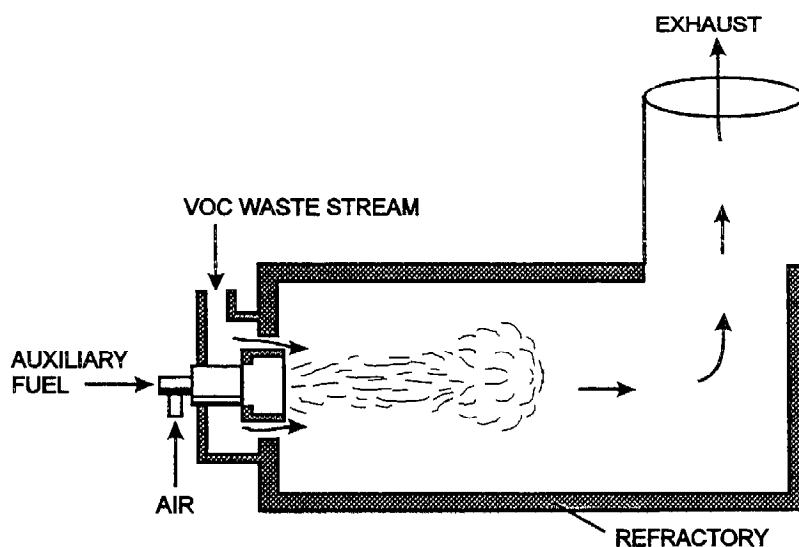


Figure 502.1 Thermal Incinerator with Horizontal Burner

temperature in the combustor high, and use heat energy from the fuel as efficiently as possible, the air and waste feed may be preheated. This heat is usually from a heat exchanger from the incinerator flue gas.

When the air, VOC wastes, and auxiliary fuel enter the incinerator, they are mixed and are then ignited by the burner. The VOCs are destroyed all through the burner flame as the hot combustion gases move toward the exit of the incinerator or oxidizer. As the gaseous feed enters the incinerator, its velocity increases as it is ignited because of the increasing temperature from combustion. The gas velocity is usually designed to be between 10 and 50 ft/sec. It is important to prevent the velocity in a thermal oxidizer from getting too low, in order to keep the ignition outside the burners and prevent the system from catching on fire.

500 INCINERATION

Some systems may use only the air in the waste stream for combustion, but others may have an additional outside air feed. Figure 502.2 shows a thermal incinerator where the waste gas enters the burner without auxiliary air. Figure 502.3 illustrates a thermal incinerator with a vertical burner where auxiliary air enters the combustion chamber through automatic dampers. The dampers open and close to help control the air fuel ratio and combustion.

It is important that the residence time in an incinerator is maximized as much as possible. Figure 502.4 illustrates how combustion efficiency increases as residence time is increased. With a longer residence time, the combustion temperature does not have to be as high and fuel requirements and costs can be reduced. A residence time of 2.0 to 3.0 seconds is recommended for most thermal incinerators.⁵

Different burner designs have been created to achieve uniform heating and prevent cold spots. A multijet burner has a series of small burners instead of one large one to increase combustion efficiency (Fig. 502.5). The thermal incinerator in Figure 502.5 also has baffles to increase turbulence within the device and provide better combustion.

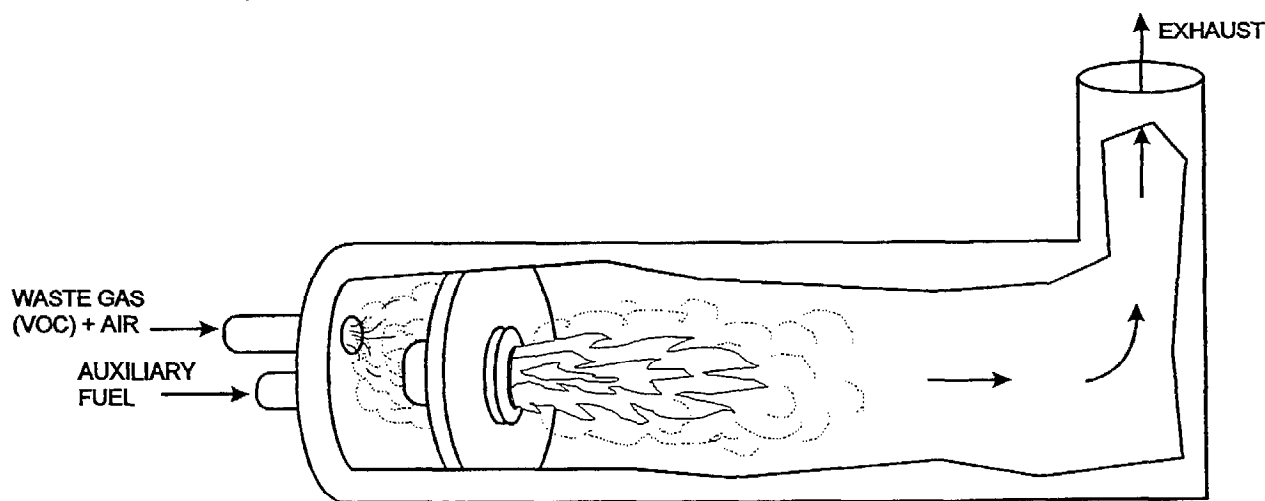


Figure 502.2 Single Flame Incinerator
without Auxiliary Air

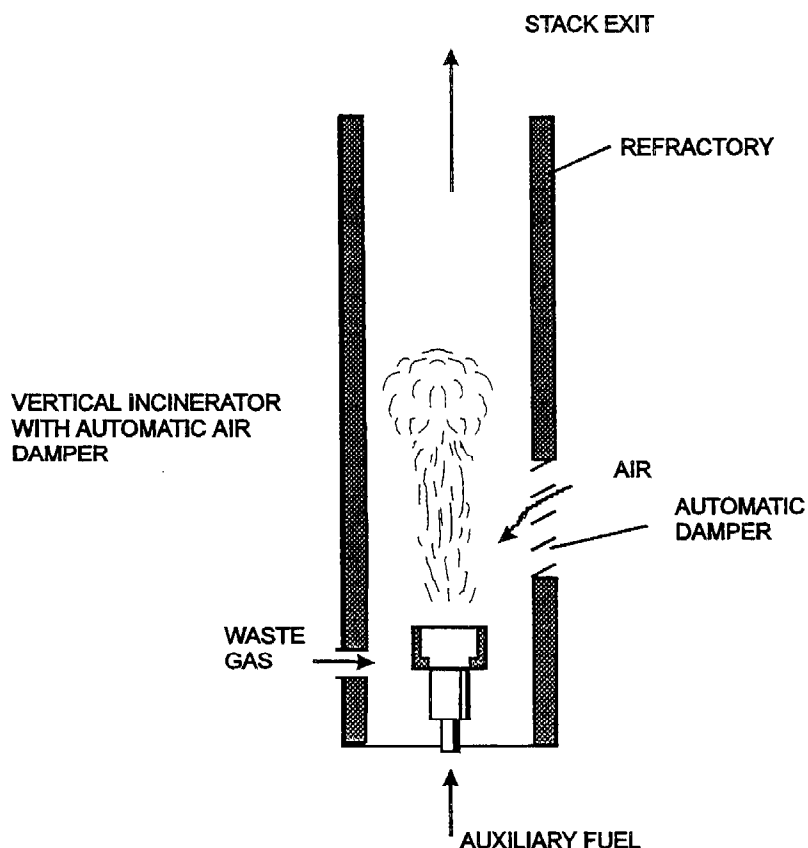


Figure 502.3 Vertical Thermal Incinerator with Air Damper

The dimensions of the combustion chamber are usually designed with a ratio of two to three.⁵ The structure of the combustion chamber is made of steel or another metal that can handle high temperatures. The inner portion of the combustion chamber is made of fire brick or a similar refractory material. The devices are often well insulated to prevent heat loss to the atmosphere.

In order to operate a thermal incinerator as economically as possible, systems are sometimes equipped with heat exchangers to recover energy from burning the fuel. The heat exchanger portion of the incinerator consists of a series of

**Combustion
Chamber
Dimensions**

500 INCINERATION

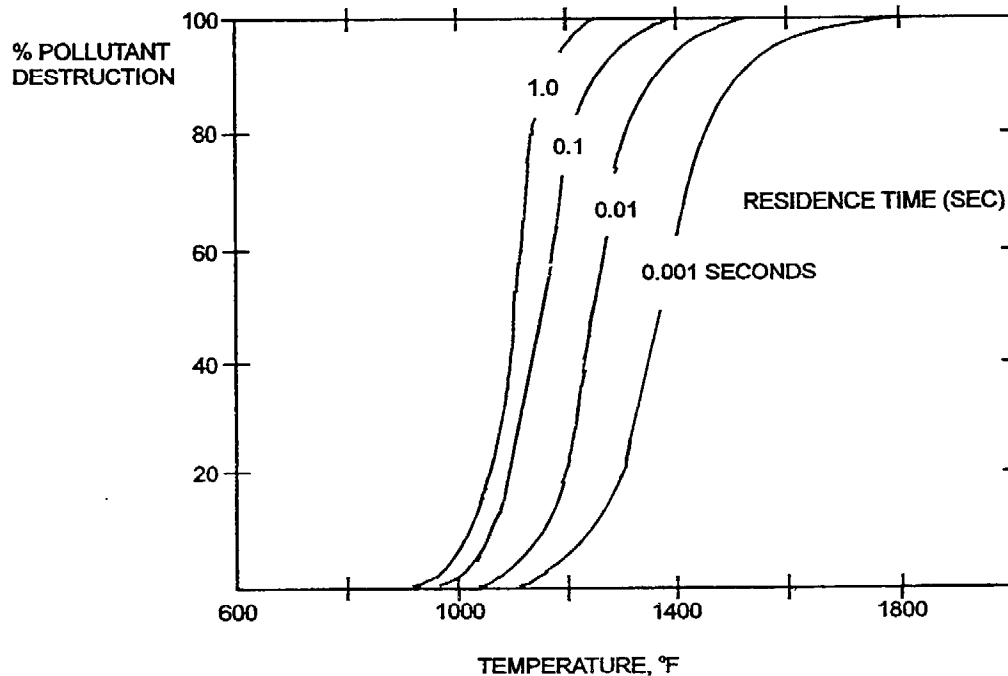


Figure 502.4 Effects of Residence Time and Temperature on Destruction Efficiency

tubes in which water flows. Hot gases pass over the tubes, heating the water. In very large units, if enough energy is recovered, steam from the heat exchanger can be used to produce electricity or mechanical energy.

502.1.1 Thermal Incinerator Problems

The biggest area of problems for incinerators handling VOCs is the burner, since it is continually exposed to high temperatures and high gas velocities. Over time, deposits can accumulate on the burner and lead to poor air/fuel mixing, an insufficient air supply and quenching of the flame on the refractory surfaces. Incinerators that are oil fired can have poor fuel atomization from deposits. Signs of poor burner performance include: lower than normal outlet temperatures and black smoke emitted from the stack.

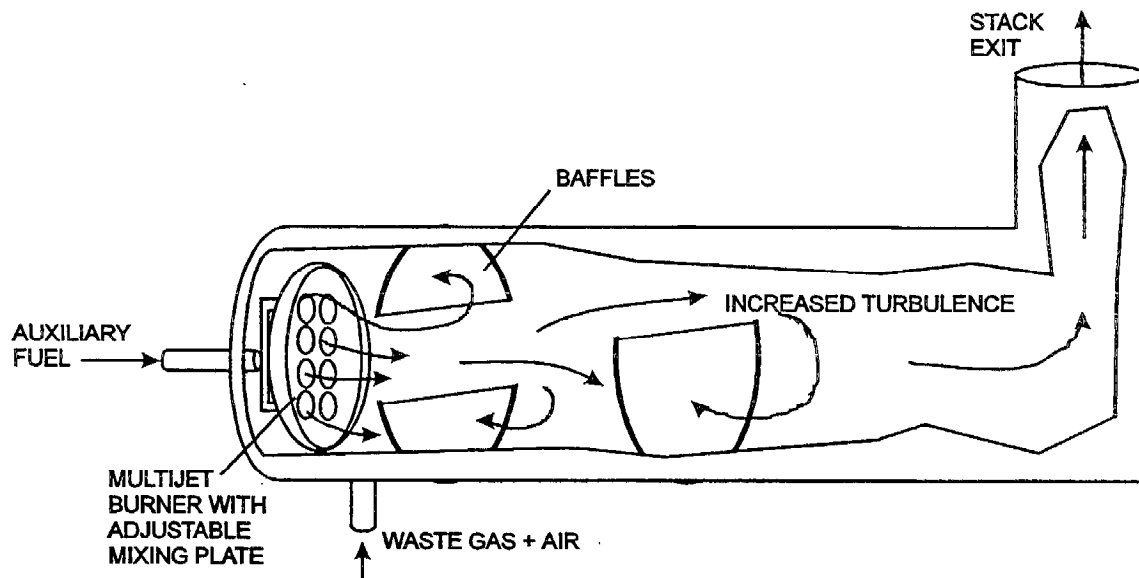


Figure 502.5 Multijet Afterburner

Rapid changes in the VOC concentration and the flow rate of the waste stream can also lead to problems. Changes in the VOC concentration and the flow rate change the fuel requirements necessary to maintain a stable outlet temperature. Sudden decreases in the VOC concentration of the waste stream coupled with an increase of the gas flow rate can lead to short periods with lower than necessary operating temperatures. If there is a sharp increase in VOC concentration in addition to a decreased flow rate, the temperature in the combustor can increase beyond the limits of the device.

502.2 CATALYTIC INCINERATORS

Catalytic incinerators differ from thermal incinerators in several ways. Catalytic incinerators have catalyst beds to oxidize VOCs (Fig. 502.6). By having a catalyst, the oxidation of VOCs can occur at a lower temperature, the reaction rate can be increased, and the combustion chamber can be smaller. Some other

500 INCINERATION

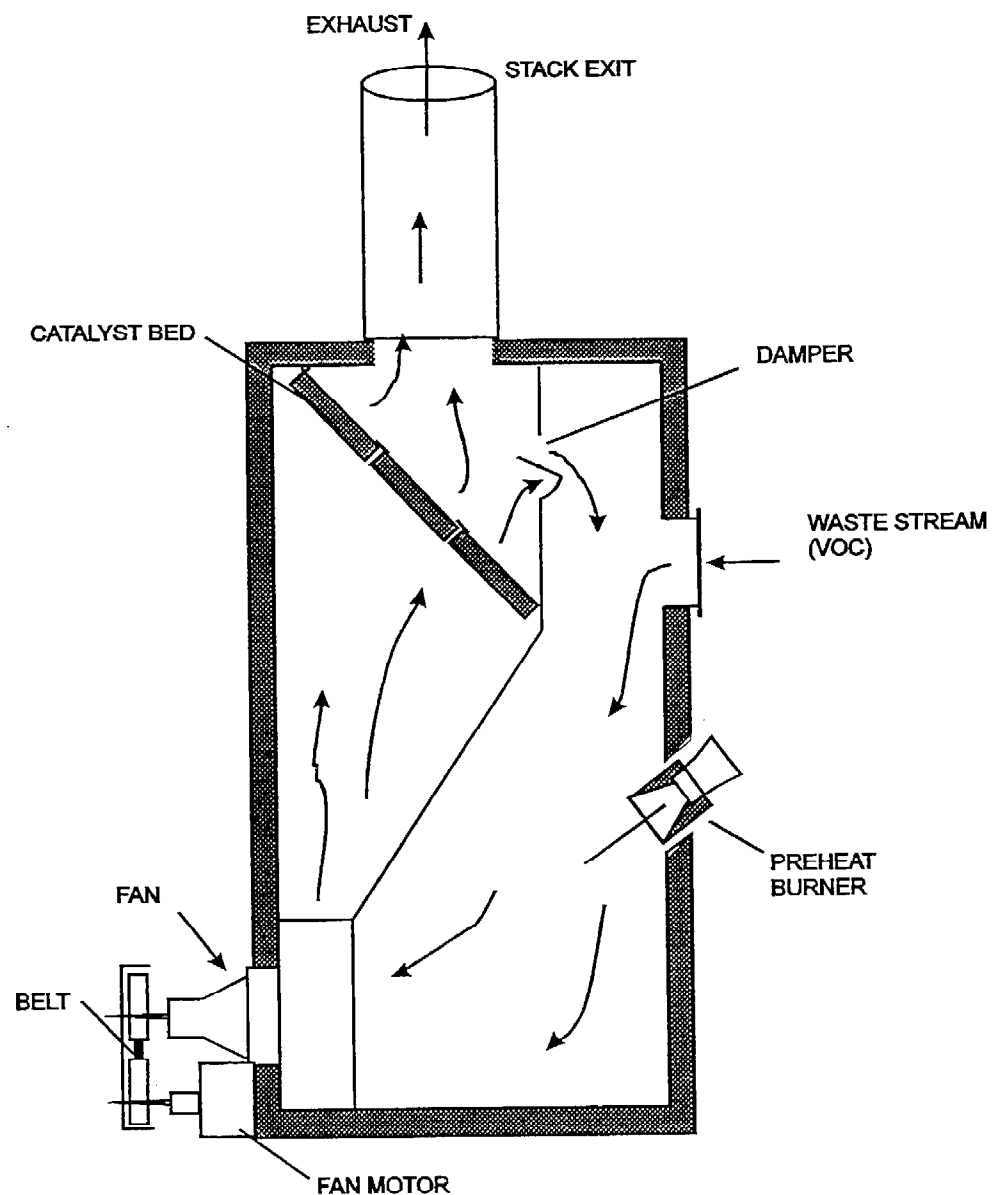


Figure 502.6 Catalytic Incinerator

500 INCINERATION

VOC Control Devices/ Scrubbers

advantages of catalytic incinerators include lower fuel usage, less insulation and reduction of fire hazards. On the other hand, the disadvantages of using a catalytic incinerator are catalyst fouling and poisoning problems, and increased costs because of catalyst replacement.

Catalytic oxidation works well for waste streams with VOC concentrations between 50 and 10,000 ppmv. Flow rates for these systems are generally less than 100,000 scfm. Catalytic incinerators should be at least 95% efficient in VOC destruction and they may achieve up to 98% efficiency.

The emission stream is preheated by a heat exchanger to approximately 600-800°F (320°C) by recovered heat from the incinerator or by an auxiliary heat source. The heat and catalyst then work to change volatile compounds to carbon dioxide and water. Below 500°F the temperature in a catalytic oxidizer may be too low to sustain adequate oxidation, and if the temperature rises above 1800°F the catalyst could be damaged. Table 502.2 illustrates typical temperatures required to destroy 90% of common VOCs.

The inlet pollutant-laden gas for both thermal and catalytic incinerators is generally limited to a VOC concentration of 500 to 7500 ppm or 25% of the Lower Explosive Limit (L.E.L.) for safety. This is done to prevent flashback of the incinerator flame into the process equipment. Table 502.1 illustrates the concentrations of common VOCs corresponding to 25% of the L.E.L. Some systems that control VOCs in a gas stream up to 50% of the L.E.L. have been developed. These systems are also equipped with continuous VOC monitors on the entrance to the device.

Catalytic incinerators can be used to control volatile compounds from a wide variety of processes. Some typical applications and temperatures are illustrated in Table 502.3.

502.2.1 Catalytic Oxidation Catalyst

Different designs of catalyst beds exist but they are generally made of ceramic or metallic materials and they are designed so that their surface area is maximized. Ceramic materials can handle high temperatures. The large surface area of catalyst beds provides a large surface for VOCs to contact. Some volatile compounds may be oxidized from the heat when in a catalytic

500 INCINERATION

| Table 502.2 Temperatures Required for 90% Oxidation of Common Compounds | |
|--|-------------------------|
| Compound | Temperature (degrees F) |
| Acetylene | 200 |
| Benzene | 300 |
| Cyclopropane | 455 |
| Ethane | 430 |
| Ethanol | 315 |
| Ethylene | 290 |
| Ethyl acetone | 415 |
| Methane | 490 |
| Methyl ethyl ketone | 370 |
| Methyl isobutyl ketone | 370 |
| n-Heptane | 300 |
| Propane | 410 |
| Propylene | 260 |
| Toluene | 300 |
| Xylene | 300 |

500 INCINERATION

VOC Control
Devices/
Scrubbers

| Table 502.3 Catalytic Incinerator Temperatures and Applications (7) | | |
|---|--------------------------------------|---|
| Process | Pollutant | Typical Operating Temperature (degrees F) |
| Asphalt Plants | Hydrocarbons, aldehydes, anthracenes | 600 to 700 |
| Carbon black production | H ₂ , CO, methane, carbon | 1200 to 1800 |
| Catalytic cracking | Hydrocarbons, CO | 650 to 800 |
| Coke ovens | Wax, oil vapors | 600 to 700 |
| Metal-lithog ovens | Solvents, resins | 500 to 750 |
| Polyethylene production | Hydrocarbons | 500 to 1200 |
| Printing plants | Solvents | 600 |
| Varnish cooking | Hydrocarbons | 600 to 700 |
| Wire coating | Solvents | 600 to 700 |

Catalyst Designs

incinerator. In order to oxidize the rest of the volatile compounds in a waste stream, the compounds must come into contact with the catalyst to be oxidized.

The catalyst bed of an oxidizer is built in the form of a honeycomb structure, a bed of spheres, pellets, or a wire mesh mat. The catalyst pellets are 1/16 to 0.5 in. in diameter, and 0.5 in. diameter pellets are most common. The pellets are porous and the porosity creates a large surface area where compounds can be adsorbed and oxidized. A catalyst with a mesh design also has a large surface area. In a wire mesh design the catalyst is in the form of a coating on the wire mesh. In general, 1.5 to 2.0 ft³ of catalyst are required for every 1000scf gases flowing through an incinerator.⁵

Sphere or pellet catalyst particles can be fixed on a bed or used in a fluidized bed. In a fluidized bed, the catalyst particles behave as a fluid as the hot gases pass through it. The catalyst is often made of a metal such as platinum, palladium or copper oxide. The catalyst helps oxidize compounds but the catalyst is not altered by chemical reactions.

When preheated organic compounds reach the catalyst, they diffuse into the pores of the catalyst material. Compounds then adsorb on the surface of the catalyst and oxidize to carbon dioxide and water. The flue gas components then flow out through the stack.

Catalytic incinerators run at lower temperatures. The temperature in a catalytic incinerator cannot get too high or the heat may damage the catalyst. The lower temperatures in a catalytic incinerator reduce NO_x formation and lower energy requirements, reducing fuel requirements.

502.2.2 Catalyst Problems

The problems that occur with the catalyst bed of catalytic incinerators include: scouring, thermal burnout, thermal aging, soot masking, particulate masking, and poisoning.

Scouring

The movement of the hot gas stream through an incinerator can eventually wear down the catalyst. This can especially be detrimental to catalysts that are composed of a coating, as in the mesh type catalyst, because they may be

worn to the point where no catalyst exist on parts of the catalyst support. This could lead to lower oxidation efficiencies.

Thermal Burnout

Thermal burnout is the volatilization of the compounds from the catalyst bed that make up the catalyst. Burnout is caused by excessively high temperatures beyond the limit the bed was designed to handle. These excessively high temperatures may be caused by undesirable increases in VOC concentration. After significant thermal burnout has occurred, the catalyst bed must be replaced.

Thermal Aging

Thermal aging is the gradual recrystallization of the noble metal catalyst materials from the high temperatures the bed is continually exposed to. Thermal aging is unavoidable; all catalyst beds with noble metals in them must eventually be replaced. With proper temperature controls, most catalyst beds will usually last three to five years.⁵

Masking

Masking occurs when material in the gas stream collects on the catalyst bed and covers it. This material will prevent volatile organic compounds from coming into contact with the catalyst, preventing the VOCs from being oxidized. Substances that collect on the catalyst are comprised of particulate matter or soot. A catalyst bed suffering from masking can be cleaned by scrubbing and washing or by using a solvent to restore its oxidation potential.

Poisoning

Some materials in a waste stream are detrimental to the catalyst bed in catalytic incinerators. Phosphorus, lead, sulfur, bismuth, arsenic, antimony, mercury, iron oxide, tin, zinc, and halogens can poison a catalyst and severely reduce performance.⁵ These compounds undergo irreversible chemical reactions with the catalyst bed and render it inactive. The bed must be replaced if a significant amount of it has been attacked by poisons. Lower than normal gas outlet temperatures are an indication of catalyst poisoning. Oxidation reactions are exothermic, so temperature increases should occur across the bed. Table 502.4 illustrates catalyst inhibitors and their effects.

500 INCINERATION

| Table 502.4 Catalyst Inhibitors | | | |
|---------------------------------|-----------------------|-----------------------|--|
| Substance | Fast Acting Inhibitor | Slow Acting Inhibitor | Effect |
| Phosphorus | X | | Irreversible reduction of catalyst activity. Reaction rate is dependent on concentration of substance. |
| Bismuth | X | | |
| Lead | X | | |
| Antimony | X | | |
| Mercury | X | | |
| Iron | | X | Same as above. Catalysts can handle higher concentrations of these poisons. |
| Tin | | X | |
| Silicon | | X | |
| Sulfur | - | - | Removable coating formed on catalyst. (dependent on temperature and concentration) |
| Halogens | - | - | |
| Zinc | - | - | |
| Organic Solids | - | - | Removable coating formed on catalyst. Coating can be removed by increasing temp. |

500 INCINERATION

VOC Control Devices/ Scrubbers

502.2.3 Factors Affecting Catalytic Incinerators

Catalytic incinerators can be affected by the operating temperature, space velocity (the reciprocal of residence time), VOC composition, VOC concentration, catalyst properties, and the presence of poisons and inhibitors in the waste stream. The higher the operating temperature, the higher the VOC destruction will tend to be. The operating temperature for a particular destruction efficiency is dependent on the composition and concentration of the VOC in the waste stream and the type of catalyst. The space velocity is defined as the volume flow rate of the combined inlet stream to the incinerator catalyst bed divided by the volume of the catalyst bed.¹⁶ The inlet stream includes the combustion air, the supplemental fuel, and the waste stream containing VOCs. The space velocity is dependent on the type of catalyst in the incinerator. At a particular temperature, if the space velocity is decreased the destruction efficiency increases. This is also the same as increasing the residence time. If the space velocity is held constant and the temperature increased, the destruction efficiency will increase.

Space Velocity

The equation for residence time is:

$$\text{Residence Time } t = V/Q$$

t = residence time (sec)

V = chamber volume (ft³)

Q = gas volumetric flow rate in combustion chamber (ft³/sec)

Residence Time Equation

502.3 BOILERS, PROCESS HEATERS, AND FLARES

Boilers are devices used to create steam. A boiler creates steam by using the energy of combustion from a fuel. The heat of combustion of the fuel is then transferred to the water through heat exchangers. Process heaters are similar to boilers, but they are used to heat streams other than boiler feed water.

Boilers and process heaters are devices that may be used for VOC destruction. Applicability of a boiler or process heater for VOC destruction depends on how VOC waste would affect their operation. The waste stream may often adversely affect boiler or process heater equipment.

500 INCINERATION

If the waste stream does not contain particulates, or any other compounds that can coat heat exchanger coils and interfere with the heat transfer in the boiler or process heater, it may be possible to use the device to handle volatile contaminants.

Furthermore, the volumes of contaminated gases must not be too large, or the thermal efficiency of the boiler or process heater will decline and pressure drops in the system will increase. The oxygen content of the waste gas must be similar to the oxygen content of the air, or incomplete combustion may form tars and resins on the surfaces of transfer equipment within the boiler or process heater. By the time excess emissions are discovered, tube fouling can become a major maintenance problem. An adequate flame must be maintained at all times to assure efficient operation.

Flares

Flares are very similar to thermal incinerators. The biggest difference between the two devices is that flares do not have a chamber for combustion. Therefore, there is no residence time in a flaring device. Flares are often a good control device to use when the concentration of organic compounds in the air exceeds the lower explosive limit.

Flares are often used in the petroleum and petrochemical industries. For more information on boilers, process heaters, or flares, please see the Petroleum Refining Technical Manual or the Utility Boilers Technical Manual.

503 RULE DISCUSSION

Federal EPA NSPS

Air pollution regulations exist at the federal level from the Environmental Protection Agency (EPA) in the New Source Performance Standards (NSPS). State laws and statutes applicable to air pollution are in the California Health and Safety Code. Specific state regulations regarding air pollution are developed by the California Air Resources Board and are included in the California Code of Regulations (CCR). Title 17 contains stationary source regulations. Applicable Health and Safety Code requirements are in Appendix B.

State ARB CCR, CHSC

Local APCDs and AQMDs

County air pollution control districts (APCDs) and multi-county air quality management districts (AQMDs) have primary authority and responsibility for enforcing regulations on stationary sources of air pollution. Districts regulate

500 INCINERATION

VOC Control
Devices/
Scrubbers

with their **rules** and by issuing **Permits to Operate** to companies owning or operating pollution generating or control equipment. Districts can also enforce the EPA rules. Many of the district regulations are similar to the EPA's, but in some cases district regulations are more stringent than the EPA's. District regulations cannot be less strict than the EPA's.

503.1 NEW SOURCE PERFORMANCE STANDARDS

The Federal Clean Air Act requires the EPA to establish new source performance standards for categories of sources which significantly contribute to air pollution. The NSPS apply both to new sources and to modifications of existing sources. The Clean Air Act directly prohibits operation of sources in violation of the NSPS. EPA has the authority to delegate enforcement to the states and has delegated primary authority to several local air districts in California. The New Source Performance Standards are located in the Code of Federal Regulations Title 40 Part 60 (40 CFR 60). The NSPS contains subparts ranging from A to VVV that give standards for a multitude of different processes. Some of these processes have VOC emission limits that can be applied to incinerators.

40 CFR 60

503.2 DISTRICT REGULATIONS AND PERMITS

503.2.1 Air Pollution Regulations

Volatile Organic Compounds

District regulations for the control of VOC emissions are usually made specific to the type of process. Some rules dealing with VOC emissions have requirements for the control efficiency of control devices (also called abatement devices). These control devices include incinerators. Regulations typically limit the efficiency by mass of VOCs. Typical control efficiencies in district rules include 85, 90, and 95%. Source tests must be done to determine if the control efficiency of an incinerator complies with the rule.

Some rules, such as those with printing and coating operations, give the maximum allowable amount of grams of VOC per liter (g/l) or pounds of VOC per gallon (lbs./gal) in ink, paint or other material. Low VOC products, which are made to comply with these rules, may not work for all applications or may

500 INCINERATION

be expensive. Regulations often allow a product with a higher VOC content in excess of rules to be used legally if it is used with a control device (such as an incinerator).

Rules for bulk plants or bulk terminals may have emission limits in terms of pounds of VOC per 1,000 gallons of organic liquid (i.e. gasoline) or also control device efficiency requirements.

Samples of coatings, inks, resins, etc. must be taken to determine if the VOC concentration complies with the rules or Permits.

The kinds of district rules that often have control efficiency requirements for control devices include:

- Storage of organic liquids
- Wastewater separators
- Bulk plant and bulk terminal operations
- Coil coating operations
- Solvent cleaning/degreasing
- Dry cleaning operations
- Surface coating of metal parts and plastic parts
- Graphic arts operations
- Rubber tire manufacturing
- Pharmaceutical operations
- Magnet wire coating operations
- Pressure relief valves at petroleum refineries
- Aerospace operations
- Semiconductor manufacturing
- Polyester resin manufacturing
- Diskette manufacturing
- Vegetable oil manufacturing
- Paper, fabric and film coating operations
- Wood products coatings
- Automotive coating operations

VOC RECLAIM

RECLAIM (Regional Clean Air Incentives Market) is a regulation that was established by the South Coast Air Quality Management District (SCAQMD). RECLAIM is basically a stationary source emission trading program where a

500 INCINERATION

VOC Control Devices/ Scrubbers

source is subject to a facility-wide mass emissions limit or "cap." Sources in the RECLAIM program are given emission allocations based on their material use and past emission history.

The SCAQMD began developing the RECLAIM program in 1991 for the control of nitrogen oxide and sulfur oxide emissions (NO_x and SO_x). The RECLAIM program officially became effective on January 1, 1994. Large sources of NO_x and SO_x have been the only sources subject to RECLAIM. In general, sources must be under the emissions cap given to them by the district, and they must reduce their emissions by 5 to 8% per year.

A RECLAIM program for VOCs has also been recently developed by the SCAQMD. A pilot program has already been conducted, but at the time of the printing of this manual, the regulation was still being drafted and small details were still being ironed out.

The advantages of RECLAIM are that it allows facilities flexibility in developing their own plans toward emission reduction goals. A facility could meet emission limits by reducing production, shutting down for a period of time, acquiring emission control equipment, using low VOC solvents, or by buying emission reduction credits from another company.

Unlike the NO_x and SO_x RECLAIM markets, the VOC market will regulate a larger number of facilities that cover many industries. Sources with over 4 tons of VOC emissions per year will be subject to the VOC RECLAIM market in July 1996. Sources between 2 to 4 tons of VOC per year would come into RECLAIM in July 1998.

Odors

Odors can be sources of public nuisances. Most districts use the Health and Safety Code Section 41700 to determine public nuisances. It states:

"Except as otherwise provided in Section 41705, (agricultural exemptions) no person shall discharge from any source whatsoever such quantities of air contaminants or other material which cause injury, detriment, nuisance, or annoyance to any considerable number of persons or to the public, or which endanger the comfort, repose, health, or safety of any such persons or the public, or which cause, or have a natural tendency to cause, injury or damage to business or property."

500 INCINERATION

The Bay Area Air Quality Management District also has a rule regarding odors (Regulation 7-300). This rule limits the amount of odorous substances discharged in the air by the amount of dilution by odor free air required and the amount of discharge that occurs. The regulation also limits emission concentrations by ppm for dimethylsulfide, ammonia, mercaptans, phenolic compounds, and trimethylamine.

503.2.2 Permits

Under the authority of the California Health and Safety Code, and in order to comply with the California State Implementation Plan and New Source Performance Standards where applicable, the districts issue Permits to Operate which contain conditions for the operation of industrial processes and emission control equipment. The conditions in Permits generally reflect the requirements of district rules that apply to a source.

Facilities must function within the parameters stated in the Permit to Operate issued by the district. Permits must be posted on the equipment, where applicable, and they must be current. If these conditions are not adhered to, it is a violation.

The equipment to which the Permit applies is listed on the Permit. It is a violation to operate pollution generating or control equipment that is not Permitted. It is also a violation to make modifications to Permitted equipment without district approval. When new equipment or modifications are required, a district will issue an Authority to Construct to the owner or operator of the equipment.

Modifications

Whenever a company must make a modification to its equipment or buy new equipment, it should notify its local district immediately. A district can usually accommodate a source even when modifications must be made in a short period of time.

ATC

An Authority to Construct will list the equipment to which it applies and it will list conditions similar to those on a Permit to Operate. After the new equipment is modified or constructed, the district may conduct a source test and issue a Permit to Operate.

500 INCINERATION

VOC Control Devices/ Scrubbers

Some typical conditions stated on a Permit to Operate include:

1. Limits on minimum outlet temperature.
2. Temperature recording equipment and temperature monitors must be installed and operating.
3. Limits on minimum residence time.
4. Limits on the type of fuel that can be used in the incinerator.
5. Limits on fuel usage per day.
6. Limits on NO_x, CO, and VOC emissions.
7. Limits on pressure drop.
8. Process limitations: types of materials used (i.e. use low VOC product for a particular printing press), amount of material used per day (i.e. gallons of solvent material - ink, coatings, resin - per day), keeping lids on solvent containers, keeping the doors on the coatings application building closed, only use acetone for cleanup, etc.
9. Recordkeeping requirements.

504 INSPECTION INTRODUCTION

Incinerator systems are inspected in order to verify that a company's equipment is designed, installed, and operating in accordance with air pollution regulations and Permits to Operate. There are four ways that the compliance status of a source can be evaluated:

1. Engineering evaluations
2. Inspections
3. Source testing
4. Continuous emission monitoring

500 INCINERATION

Reasons for Inspection

Of these, only the first and third provide actual emission data as to the extent of emissions from a facility. Inspections will primarily be the focus of this section, but source testing and continuous emission monitoring shall be briefly discussed.

Inspections of incinerator/oxidation systems may be performed for any one of the following reasons:

1. Compliance determination
2. Complaint investigation as a result of excess emissions or equipment malfunction
3. Source plan approval
4. Review or renewal of Permits
5. Special studies

Examples of special studies would be operating and maintenance evaluations, or updating emission inventories.

Compliance-type inspections only provide preliminary emissions assessments. Source testing is the method of determining compliance with an emission standard. Compliance inspections are usually unannounced so that a facility can be evaluated under normal operating conditions. Such indicators as waste charging, continuous monitoring, and visible emissions, which can be estimated during an unannounced inspection, often provide a definitive picture of a process using an incinerator, provided there are no access problems or faulty and/or inoperative equipment.

For other inspections pertaining to source construction, plan approval, Permits to Operate, or "baseline type" inspections, the plant should be given sufficient advance notice so that qualified plant personnel can be present to provide the drawings, manuals, and process information that may be required. Prior notice should also be given when performing inspections for special studies designed to document operating and maintenance practices, or process and emission data. This will allow the operator time to make readily available information such as raw material rates, production levels, and stack test results. Regardless of the type of inspection to be conducted, pertinent supporting information should be obtained prior to, during, and following the source evaluation.

500 INCINERATION

VOC Control
Devices/
Scrubbers

One of the best ways a source can stay in compliance with air pollution regulations is through preventative maintenance inspections. Companies that have efficient inspection and maintenance (I&M) programs tend to have fewer breakdowns, require fewer variances, have less down time and can save money. With an efficient I & M program, problems with equipment can be anticipated and surprising catastrophic failures can be reduced. A good I & M program also requires that neat, orderly, consistent records of self-inspections be kept by the company. Local districts can usually assist sources with I & M programs.

I & M

504.1 SEQUENCE OF INSPECTION

The sequence of an inspection is a question of what order to inspect the equipment in a process. The two main logical sequences to follow are a co-current and a counter-flow approach, but regardless of the type of sequence chosen, it is usually best to first inspect the outside of a facility. By inspecting the perimeter of a plant an inspector can see if there are any illegal emissions or odors crossing the plant's boundary before the source is aware of an inspector's presence.

504.1.1 Co-Current Approach

The inspection of a incinerator system using a co-current approach is conducting the inspection in the same general direction as the flow of the gas stream. The general sequence would be the process, the capture system, the control device, and the stack. An inspector may want to use this type of approach when he is unfamiliar with some process details and would like to observe them before seeing the equipment.

504.1.2 Counter-Flow Approach

An inspection with a counter-flow sequence is conducted against the direction of gas flow. An inspection of this type would generally begin at the stack and continue to the control device, capture system and then the process. The advantage of this approach is that an inspector may be able to more quickly identify where an emission problem originates.

500 INCINERATION

504.1.3 Other Approaches

In some instances an inspector may not start at the stack or the process or the beginning or end of a system. If observations of possible illegal emissions were made while outside the facility, an inspector may want to head directly to the source of the emission. If an inspection is a strict, unannounced compliance-type, or if an inspector is very familiar with the process and only has a particular item to deal with, the inspection could start and finish in a different manner.

504.2 LEVELS OF INSPECTION

Four different levels of inspection have been developed by the U.S. EPA. A level 1 inspection consists of an inspection that is the least in-depth and a level 4 inspection is the most in-depth. The levels are inclusive; a level 3 inspection, for example, would also include all the items done in a level 1 and level 2 inspection. Although these levels may not be always strictly adhered to in practice, the levels help organize all the means in which a system can be inspected. In a level 1 inspection an inspector conducts a visible emissions evaluation outside the facility. In a level 2 inspection an inspector conducts a walkthrough evaluation of the control device and process equipment. All the data acquired in a level 2 inspection is acquired from on-site gauges. In a level 3 inspection, independent measurements of operating conditions separate from the existing on-site gauges are conducted. This is usually done when the existing on-site gauges are inadequate. A level 4 inspection is performed by agency supervisors or senior inspectors to acquire baseline data. As with the level 3 inspection, independent monitoring equipment is used for the level 4 inspection. The "baseline" data acquired in past level 4 inspections is used by inspectors to check the operation of process equipment.

505 PRE-INSPECTION PROCEDURES

It is important to prepare for an inspection prior to your visit to the facility. Rules and Permits can be very complicated and preparations must be made for a successful inspection. This section is a discussion of some general guidelines on what steps to follow prior to the inspection.

500 INCINERATION

VOC Control
Devices/
Scrubbers

505.1 FILE REVIEW

Prior to the site inspection, the inspector should review all information available in the district source files including: approved Permits, equipment lists, conditions for each Permit, previous inspection reports, Notices of Violation, breakdown reports, enforcement actions taken, odor complaints, variance histories, alternative emissions control plans, abatement orders, source tests, and the design of the process and incinerator/oxidizer system.

Verify that all applicable Permit(s) are current and valid. Bring a current copy of the Permit(s) with you and bring extra copies in case the source has misplaced or lost their copy.

The inspector may wish to complete some portions of the inspection documentation before arriving at the facility, as this will save time during the pre-inspection meeting. If your district has checklists or rule specific forms, use them.

505.2 REGULATION REVIEW

You should review any references to the specific rules which are noted in the source files. In particular, be familiar with each standard and exemption in the rules. Discuss regulations with experienced personnel and review any policies your district may have. Make sure that you receive consistent interpretations on how to apply the requirements of rules.

505.3 EQUIPMENT CHECK

Make sure that you have the following equipment available for use during the inspection: vision protection, hearing protection, safety shoes, hard hat, gloves, identification, business cards, pens, wipes, inspection forms, chain of custody forms, sampling cans, can case, labels, and thermometer.

500 INCINERATION

505.4 PRE-ENTRY AND ENTRY

When you arrive at the facility, notice if there are any strong odors or visible emissions. If there are any odors or visible emissions, make sure you document them and plan on finding the sources as soon as possible after entering the facility.

Request to see the previous contact mentioned in the files. Depending on the facility, it may be the environmental coordinator, supervisor, president, maintenance worker or operator. Always present your business credentials immediately to avoid confusion.

If the source is unfamiliar with your district's authority, be prepared to cite and provide copies of California Health & Safety Code (CHSC) Section 41510: Right of Entry (a copy is available in the Appendix). Know and follow your district's policy if the facility refuses entry.

505.5 PRE-INSPECTION MEETING

Before the inspection begins, the inspector should meet with the source representative to obtain operating information. The inspector should state the purpose of the inspection and identify the equipment which will be inspected. Facility information can be verified during this meeting, including: the facility name and ownership, address complete with city and zip code, contact name, contact title, phone number and area code. Discuss safety procedures and whether or not there have been any odor problems in the past. Request a copy of material safety data sheets (MSDS), and if necessary discuss sampling procedures. Check existing Permit conditions and ask if any changes have been made to the operation which are not reflected in the Permit.

The district's equipment list on the Permit to Operate should be compared to the facility's Permit to Operate. The items should be the same. If they are not, a Notice of Violation may have to be issued. Also, check existing Permit conditions and ask if any other changes have been made to the operation which are not reflected in the Permit.

500 INCINERATION

VOC Control
Devices/
Scrubbers

506 INCINERATOR INSPECTION

506.1 VISIBLE EMISSIONS

Observe the exhaust coming from the stack of the incinerator. A well operating unit should have no visible emissions, but the opacity limit in most districts is 20%. The Permit could limit the incinerator to no visible emissions. Some "waviness" may be visible from the heat coming from the stack. Visible emissions may be an indication of poor burner operation or the condensation of unburned organic compounds.

506.2 INCINERATOR BYPASS STACK

Some incineration systems may be equipped with a bypass stack for safety. In case of an incinerator malfunction, volatile organic compounds will be vented through the bypass stack and into the environment. Under normal operating conditions, no emissions should be emitted from the bypass stack. Leaks can occur from a poorly sealed bypass damper. Check for leaks from the bypass stack by looking for "waviness" emitted from the bypass stack.

506.3 INCINERATOR SHELL AND DUCTWORK

Check the ductwork and shell for corrosion. The shell, stack and outlet are vulnerable to corrosion, especially if there are chlorinated hydrocarbons in the waste stream. Hydrochloric acid can form in the combustion process and attack the ductwork or shell. The corrosion cannot be to the extent where it compromises the structural integrity of the device; no holes should be in the shell or ductwork.

Listen for air infiltration, especially if the incinerator is under negative pressure with a fan downstream of the control device. Air infiltration will be occurring in a negative pressure system if any holes are in it. Air infiltration can lead to incomplete VOC oxidation. Severe air infiltration can lower incinerator temperatures below the minimum required for proper operation. Air infiltration can also lower capture efficiency at the hood.

500 INCINERATION

506.4 INCINERATOR OPERATING TEMPERATURE

For thermal incinerators and boilers the combustion chamber temperature should be recorded. If the temperature is lower than the baseline value, it could mean a lower VOC destruction efficiency; if the temperature is lower than the minimum temperature on the Permit, it is a violation. The temperature may be recorded from a gauge on the device or the control room.

For catalytic incinerators, the temperature of the gas stream at the inlet and outlet to the catalyst bed should be recorded. The inlet temperature should be measured after the preheat burner, and the outlet temperature should be measured upstream of any existing heat exchangers for energy recovery. The temperature across the catalyst bed should increase. Smaller than normal temperature increases could mean problems with the catalyst bed. Check temperatures with baseline values and Permits.

506.5 FAN MOTOR CURRENT AND STATIC PRESSURE

If the system is equipped with a fan, find any existing gauges measuring the fan motor current. If there are any gauges for the current, record the value and check it with the baseline value or Permit. Lower fan currents indicate a lower volume flow rate.

If the incinerator system is equipped with a hood, record the static pressure. The static pressure should be within the limits on the Permit.

506.6 PROCESS EVALUATION

Check and record all relevant information from the process including pressures, temperatures, flow rates, and materials used for the process. See if the information is in agreement with the Permit to Operate. Make sure the incinerator was running all the time that the process was in operation; verify this from the facility's records.

500 INCINERATION

VOC Control
Devices/
Scrubbers

**Table 507.1
INCINERATOR INSPECTION FORM**

| <u>Pre-Inspection:</u> | <u>Field Inspection:</u> |
|--|---|
| Facility name: Unit I.D. number: | Date/time: |
| Permit number: Permit expiration date: | Inspector: Agency: |
| Facility address: | Facility contact person(s)/title(s): |
| Date unit was built or last modified: | |
| Overall Incinerator Condition | |
| Incinerator type: thermal incinerator, catalytic incinerator, flare, process heater Does the incinerator have heat recovery? Does the incinerator have a catalyst bed? How often should it be replaced? | Any excessively corroded or rusted equipment? Any holes or gaps in incinerator shell or ductwork? Any visible emissions or excessive odors? When was the catalyst last replaced? |
| Gauges and Monitors | |
| Is the incinerator equipped with a continuous emission monitor? | VOC outlet concentration: |
| Maximum permissible outlet concentration: | Incinerator inlet temperature: Incinerator outlet temperature: |
| Minimum outlet temperature: | Pressure drop: |
| Maximum pressure drop: | |

506.7 VOC OUTLET CONCENTRATION

Measuring the outlet VOC concentration is a part of a level 3 or 4 inspection; it is not part of a typical inspection of an incinerator. In a level 2 inspection VOC emissions may be found from continuous emission monitors. If the unit is also equipped with a chart recorder, the records should be copied. Also copy calibration records from the continuous emission monitors. The concentration of VOCs in the outlet steam can only be measured if it is safe. Convenient and safe measurement ports must be available. Ports should be as far downstream as possible so the gas stream will not be too hot. In a level 4 inspection these ports would have to be installed. If the temperature of the gas stream is over 300°F it may be necessary to include a condenser and knockout trap on the sample line to protect the VOC detector from the heat. The VOC detector and any portable recorder used with the instrument must be certified as intrinsically safe. This means they must be certified not to be able to ignite a fire or explosion when used properly.

The concentration of VOCs on the inlet side of the incinerator can be measured in a similar manner. No knockout trap or condenser should be necessary since the gas stream will be cooler (under 250°F). A dilution probe may be necessary for photoionization and flame ionization detectors limited to a maximum reading of 1000 to 2000 ppm.

Once the inlet and outlet concentrations are determined, the efficiency of the control device can be determined. Only 5 to 10% of the VOCs in the inlet gas stream should be left in the outlet gas stream.

506.8 MEASURING THE OUTLET TEMPERATURE (LEVEL 3 AND 4)

The temperature on the outlet side of an incinerator can be measured similarly to the VOC concentration through safe convenient ports, especially if the readings from existing gauges are inaccurate. However, this is typically not done by district inspectors in regular inspections. Measuring the temperature with portable instruments has several problems. The temperature read from portable instruments may be higher than normal because of radiant energy from the incinerator. Baffles can cause temperature readings to be lower than they actually are if they tend to shield the probe when the temperature reading is taken.

500 INCINERATION

VOC Control
Devices/
Scrubbers

507 POST-INSPECTION PROCEDURES

Prior to leaving the facility, the inspector should evaluate the compliance status of the plant and should have obtained all the information necessary to complete inspection forms.

The facility should be informed of the results of the inspection, advised of areas of concern where additional information or investigation is needed, or given a Notice of Violation (NOV) as soon as possible. Be prepared to make your compliance determinations, calculate excess emissions, and issue all necessary violation notices. Be able to document future NOVs which may be pending due to sample results or additional information requests. **All violations should be followed up**, consistent with your district policy, to ensure that the source is brought into compliance. Always update the Permit file with the actions that took place during and as a result of the inspection.

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

This section is primarily a discussion on scrubbers used to control particulate matter, but cyclones will also be discussed. Scrubbers that use a liquid (usually water) to control particulates are also called wet collectors or wet scrubbers. There are different types of devices that are called scrubbers, but in this section of the manual, "scrubber" refers to devices that perform wet collection and absorption.

Absorbers, which were discussed in Section 300, are sometimes also called scrubbers. In air pollution control, gas absorption is removing a gaseous pollutant from an air stream by dissolving the pollutant into a liquid. Absorption does occur in a scrubber, but it is not the primary means of particle collection in a scrubber. Some of the material presented in this section also applies to absorption, especially the section on flue gas desulfurization.

601 INTRODUCTION

Particulate matter emissions have been controlled since the early stages of the Industrial Revolution. By the 1600's people noticed that particulate matter had adverse effects on buildings, fabrics, and other materials. As technology improved and particulate emissions increased, it became apparent that particulate matter adversely affected health. One of the earliest patents for a particulate control scrubber was issued in 1901. By 1935, scrubbers with 98% efficiency were being used to remove SO₂ from flue gas.

Particulate matter is small particles of material that can easily become airborne. The burning of wood, fossil fuels, agricultural operations and photochemical reactions are a few of the sources of particulate pollution. The greatest concern is for the very small particles that are less than 10.0 micro meters (10.0×10^{-6} meters) in diameter, since these particles can easily bypass the lung's natural filtering system. Particles of this size are also called "PM-10." Micrometers may also be abbreviated as " μm " or are simply called "microns."

PM-10

601.1 HEALTH EFFECTS OF PARTICULATE MATTER

Short term exposure to particulate matter can lead to coughing and throat irritation. Inhaled particles can irritate the respiratory tract, constrict airways and interfere with the mucous lining of the airways. Longer term exposures can

600 SCRUBBERS

State Standards

lead to increased chances of developing bronchial disease, a disease of the lungs. Particulates can be composed of metals and toxic compounds or they may carry carcinogens such as dioxin or benzene. These particles can get deep into the lungs and increase the probability of cancer. The EPA now also believes that inhaling particulate matter contributes to up to 60,000 deaths a year.

Particulate matter is a form of pollution that adversely reduces visibility. Some forms of particulate matter can damage the surfaces of buildings, the finishes of cars and other objects.

The state standards for particulate matter are $30 \mu\text{g}/\text{m}^3$ averaged over a year and $50 \mu\text{g}/\text{m}^3$ averaged over 24 hours. The only air basin in the State of California that is in attainment of the state standard for particulate matter is Lake County (Fig. 601.1).

Baghouses or electrostatic precipitators may often be a better control device, depending on the application, but scrubbers have several advantages. Some of the advantages of scrubbers are that they have a constant pressure drop, they can handle high temperature flue gases, they can handle moisture laden gases, they can handle corrosive gases, and there is no problem with dust disposal.

601.2 SOURCES OF PARTICULATE MATTER

Particulate matter is emitted into the air by a variety of natural and man-made sources. Most of the particulates that get into the earth's atmosphere are from natural sources, but human activities are the main source of particulate matter in urban areas, where most people are exposed to it. Man-made sources of particulate are of greatest concern, since they are a greater health risk and more people are exposed to man-made particulates. People in rural areas can also be exposed to particulates from farming activities, poor weather conditions, and transport from urban areas.

AREA DESIGNATION
FOR STATE AMBIENT
AIR QUALITY STANDARD

PM10

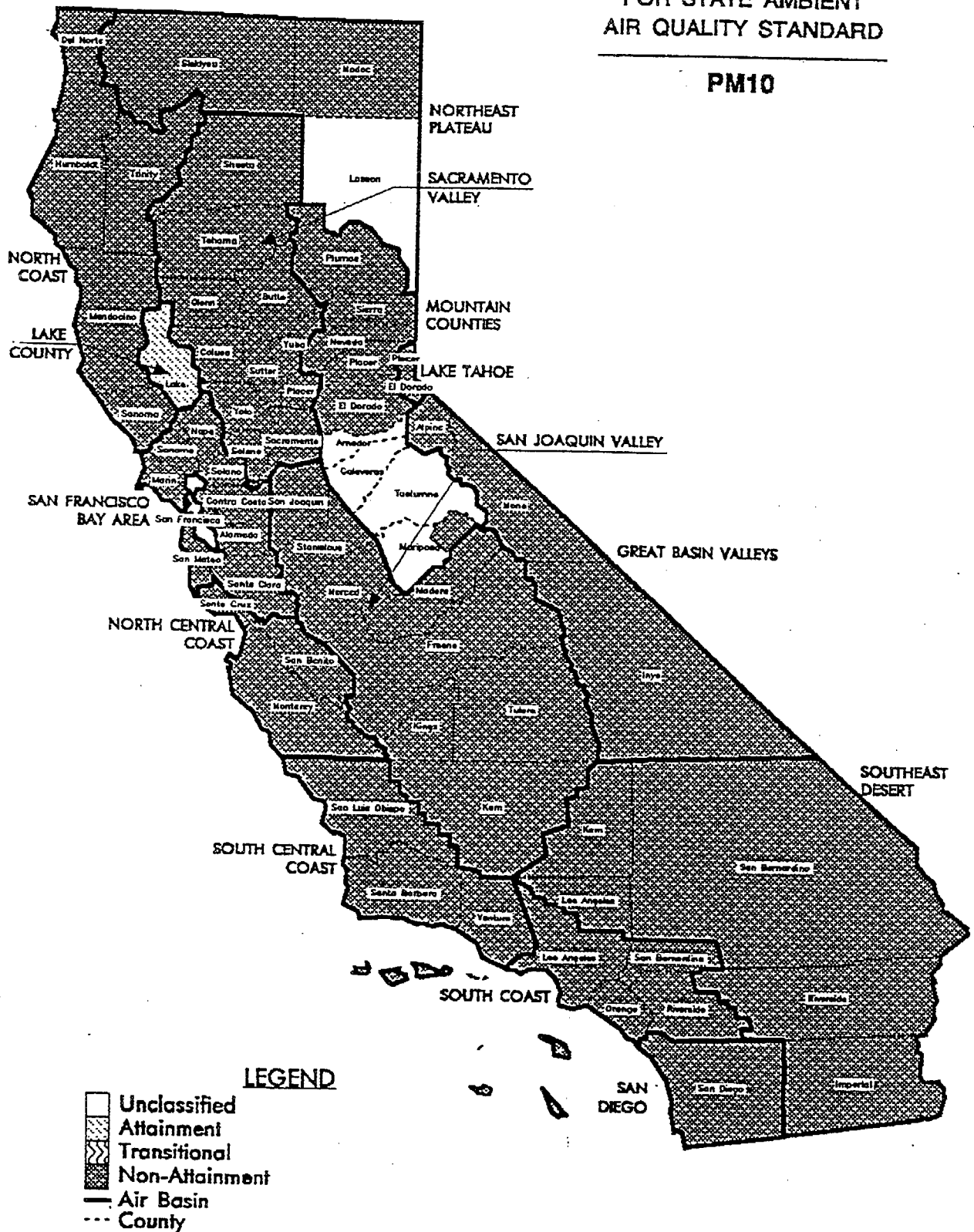


Figure 601.1 Suspended Particulate Matter

600 SCRUBBERS

The major sources of natural particulate matter include forest fires, soil debris, volcanoes and ocean salt spray. Some forest and brush fires can be man-made. Agricultural burns are also a source of particulate matter.

Fugitive dust is a type of particulate matter that originates primarily from human activities disturbing the soil. Unpaved roads, farming, construction, off-road vehicles, and mining are some of the major causes of fugitive dust.

The major categories of man-made sources of particulate matter include stationary fuel combustion, industrial processes, and solid waste disposal. Combustion from stationary sources is responsible for 35 to 50% of the total particulate matter from man-made sources.¹ These sources typically include fossil fuel fired boilers at power plants. Industrial facilities such as steel mills, refineries and manufacturing plants are responsible for approximately 40% of the man-made emissions.¹ This manual deals with the control of particulates from these sources.

Particulate matter can be directly emitted into the atmosphere or it can be created in the atmosphere from photochemical reactions. Sulfur dioxide emissions and nitrogen oxide emissions into the atmosphere can later develop into sulfate and nitrate particles respectively through chemical reactions.

602 PARTICULATE CHARACTERISTICS AND FORMATION MECHANISMS

602.1 PARTICLE SIZE

Particle sizes that are of interest in air pollution control range between 0.1 and 1000 microns in diameter. Typical raindrops, for example, are approximately 500 microns in diameter. Particles can also be so small that they may be made of fewer than 50 molecules, and the smallest stable particles can be composed of only 20 molecules. Particles this small cannot be seen by sensitive light microscopes.¹ Individual gas molecules are 0.0002 to 0.001 microns in diameter, but particles of this size range tend to rapidly agglomerate into particles over 0.1 microns in diameter.¹ Only a very small amount of particulate matter in the 0.01 to 0.1 micron range make it to a control device.

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

The particle volume between a 0.1 and a 1000.0 micron particle differs by a factor of 10^{12} or, in other words, 1000 micron particles have a volume one trillion times larger than a 0.1 micron particle. If, for example, a 1000 micron particle was the size of a large, domed sports stadium, a basketball in this stadium would be equivalent to a 5 micron particle. Approximately 100,000 spherical 0.1 micron particles would then fit into the 5 micron "basketball."¹

Figure 602.1 shows the relative size between a 1 micron particle, a 10 micron particle and a 100 micron particle. Approximately 50 particles strung together with a diameter of 1 micron are equivalent to the diameter of a human hair. Particles under 10 microns in diameter are of greatest concern since they can get through the lung's natural cleaning mechanisms and deposit deep within the lungs. A large portion of particulate matter generated from industrial processes is less than 10 microns in diameter. Particles in the 1 and 10 micron range are generally considered to be in the "moderate" size range in air pollution control. Particles that are less than 1 micron in diameter are considered to be in the "submicron" range. Submicron particles are considered to be small particles in air pollution control and are the most difficult to collect.

602.2 PARTICLE SHAPES

Although in many air pollution applications particulates are often thought of as perfect spheres, in the real world particulates come in many shapes (Fig. 602.2). Solid, irregularly shaped particles are usually created by processes using a grinding action. Hollow, spherical shaped particulates are often created in high temperature combustion processes. Particles that are in the form of fibers are usually asbestos or another fibrous mineral. Particulate emissions of asbestos fibers can be emitted from asbestos material undergoing continuous movement or deformation, allowing fibers to break away from the material.

The diameter of irregularly shaped particulates can be defined by the Martin's diameter or the Feret's diameter. Martin's diameter is simply the diameter of a particle where the particle would be divided into two equal masses. Feret's diameter is the maximum edge to edge distance of a particle (Fig. 602.3).

Particle Diameter

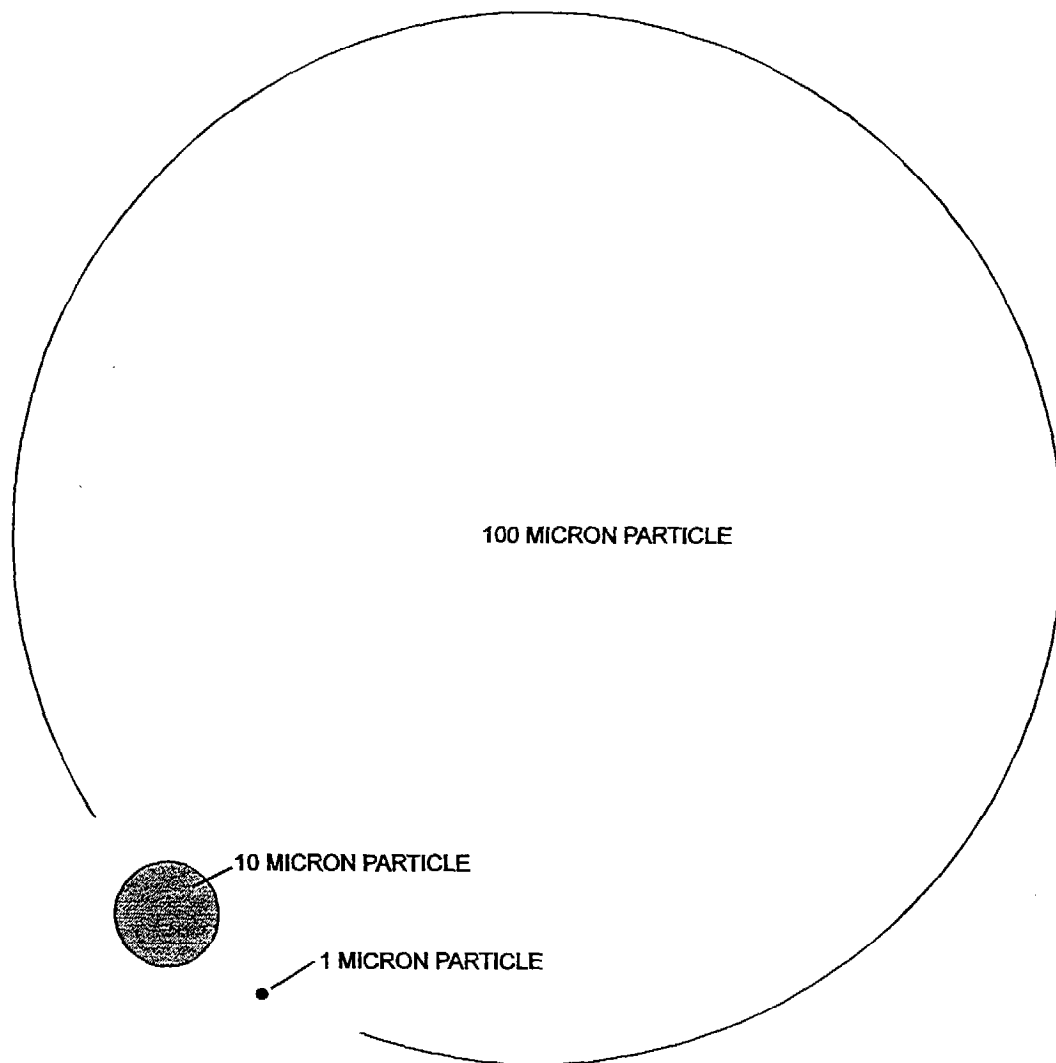


Figure 602.1 Relative Size of 100,
10 and 1 Micron Particle

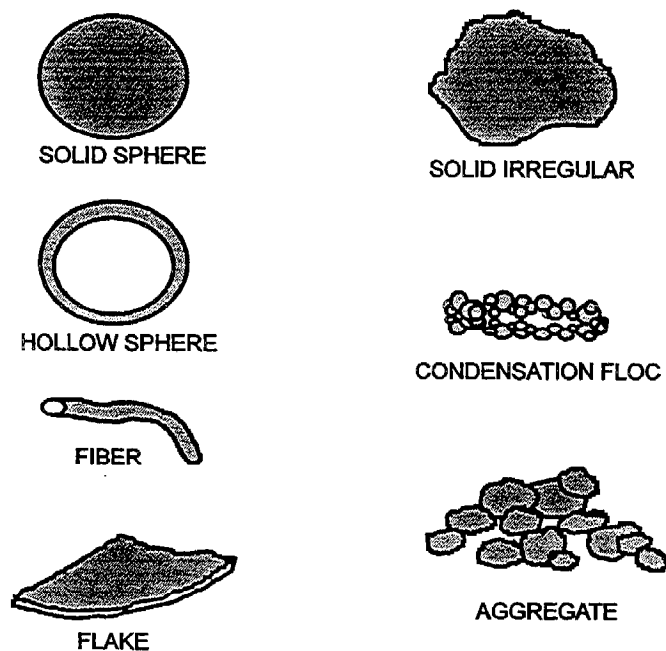


Figure 602.2 Particle Shapes

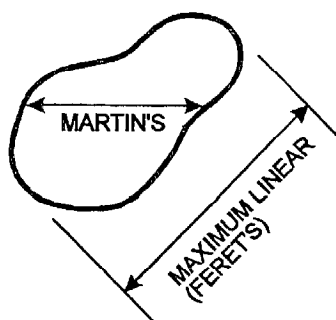


Figure 602.3 Martin's Diameter and
Feret's Diameter

The Martin's diameter and the Feret's diameter are not related to how particles behave in air, so another parameter, the aerodynamic diameter, has been developed. The aerodynamic diameter takes into account a particle's density.

$$dp_a = dp(\rho_p C_c)^{0.5}$$

where:

dp_a = aerodynamic diameter (μm)

dp = actual diameter (μm)

ρ_p = particle density (g/cm^3)

C_c = Cunningham slip correction factor (dimensionless)

(C_c can be estimated by: $C_c = 1 + [(6.21 \times 10^{-4})(T)]/dp$)

where T = temperature, degrees Kelvin)

Particles can be shaped very differently but have the same aerodynamic diameter, but on the other hand, particles can have the same shape and have different aerodynamic diameters. The aerodynamic diameter of a particle is not its true size, but it is a means of categorizing how certain particles move in a fluid.¹

602.3 PARTICLE FORMATION

The main particle formation mechanisms include:

- Physical attrition/mechanical dispersion
- Combustion particle burnout
- Homogeneous nucleation
- Heterogeneous nucleation
- Droplet evaporation

Physical Attrition

The sizes of particles formed from a process is very dependent on the type of process and the formation mechanisms present. Physical attrition occurs when two surfaces are rubbing against each other. Particulates created from grinding, scraping, pulverizing, crushing, and similar processes are created by attrition. Particulates created from attrition tend to be larger in size. The energy involved in grinding operations is too low to create a large amount of very small particles. Particles created from grinding operations will have the same density and composition as the material before it was ground.

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

Before injection into a combustion chamber, liquid fuels, such as oil, are atomized into small droplets, and solid fuels, such as coal, are pulverized into small chunks so they will burn rapidly and completely. When the fuel is injected into the combustion chamber, the volatile substances in the fuel are initially vaporized and then oxidized, releasing energy. After volatile materials are driven from a liquid or solid fuel, ash and char still remain. Ash is incombustible material and char is slow burning organic compounds. Most of the char may still burn during the combustion process, but ash and any remaining char can become particulate emissions when they exit the exhaust.

Homogeneous nucleation and heterogeneous nucleation involve the conversion of vapor phase materials to solid particles. During homogeneous nucleation, new particles are created from gaseous substances, but during heterogeneous nucleation, material collects on the surface of particles that are already in existence. Homogeneous and heterogeneous nucleation occur when substances in exhaust gases after combustion cool to their dewpoint and condense. The gaseous materials that condense upon cooling include organic compounds, metals, and metal compounds. Some metal compounds that may nucleate include mercury, lead, cadmium, and arsenic. Many of these compounds are toxic; therefore, particulates can become carriers of toxic compounds.

Homogeneous and Heterogeneous Nucleation

Metal compounds tend to nucleate first after a combustion process since they have higher dewpoints. As hot flue gases cool further as they flow through heat exchange equipment, organic compounds begin to condense. The condensation of different compounds on the surfaces of particles can create particles covered with different layers of material. Particles created by homogeneous and heterogeneous nucleation are very small, ranging from 0.05 to 1.0 microns.

Droplet evaporation is a particulate formation mechanism that occurs when recycled water from a scrubber system containing dissolved solids from capture of particulates is injected into a chamber with hot combustion gases. As water is injected into a chamber, it is atomized into small droplets by spray nozzles. The hot combustion gases may cause the water droplets to evaporate, leaving particles suspended in the air stream. This type of particle formation mechanism may create particles between 0.05 and 20 microns in diameter.

Droplet Evaporation

603 PARTICULATE COLLECTION MECHANISMS

All particulate control devices generally share the same steps in the removal of particulates from a gas stream. These steps include the initial capture of particles, gravitational settling and cleaning, and solids removal. The initial capture step involves the use of inertial forces or electrostatic forces or both on particles, so they will leave a gas stream. In scrubbers, particles are initially captured in droplets or sheets of liquid. The gravitational settling step involves the removal of dust cakes from the bags of baghouses, the plates of electrostatic precipitators (ESPs), and the collection of entrained droplets in a scrubbing system. Solids removal in baghouses and ESPs is done through hoppers, and in scrubbers solids are removed from the scrubbing liquid.

The main method in which particulates are removed from a gas stream with a scrubber occurs in several parts. First, particulates are wetted by contact with liquid droplets. Then the wetted or unwetted particles are impinged on collecting surfaces or settle out by gravity. The particles are then removed from the collecting surfaces by a flush with a liquid.

The main collection mechanisms used to remove particles from a gas stream are inertial impaction, interception, Brownian displacement, gravitational settling, electrostatic attraction, thermophoresis, and diffusiophoresis. These mechanisms are used to force particles out of gas streams. The higher the force that can be applied to a particle, the easier it is to remove the particle from a gas stream. This can be illustrated by Newton's Law $F = ma$ where "F" is force, "m" is mass, and "a" is acceleration. The higher the mass of a particle at a given acceleration, the higher the forces will be on the particle. Furthermore, the higher the acceleration is on a particle of a given mass, the higher the force acting on the particle will be. Larger particles will tend to have a larger mass. Therefore, all of the collection mechanisms are very dependent on particle size. The smaller particles are, the harder they are to collect, until their size is below 0.3 microns. Particles that are just over 0.3 microns in diameter are the most difficult to collect. Below 0.3 microns, particles tend to agglomerate.

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

603.1 INERTIAL IMPACTION

Impaction is the mechanism that removes most of the particulate matter in a scrubber. In order for impaction to occur between a liquid droplet and a particle, the particle must have enough inertia to continue in a straight line to impact with a liquid droplet. Particles collected by impaction have too much inertia to follow the gas stream lines around a water droplet (Fig.603.1). Particles that have a larger mass have more inertia. The kinetic energy of a particle hitting a droplet helps overcome the surface tension of the droplet so that the liquid droplet can engulf the particle.

Impaction works more efficiently when there is a large difference in velocity between the water droplets and particles. In a scrubber, the particles in a gas stream are usually moving much faster than the water droplets. Impaction is very efficient for particles larger than 10 microns in diameter, but it is not efficient for particles less than 0.3 microns in diameter.¹ Small particles will have a low inertia because of their small mass. If a very small particle hits another particle it may rebound off the particle. Small particles may not have enough inertia to overcome the surface tension of a water droplet. Surface tension is the "skin" that seems to appear on the surface of a liquid. It develops from the intermolecular cohesive and adhesive forces (van der Waals forces) between molecules of water. Surface tension increases as the temperature of a liquid is lowered. At 68°F water has a surface tension of 0.004985 lbf/ft.

Impaction is analogous to trucks and cars on a freeway. The trucks and cars will have a high chance of hitting each other if they have very large differences in velocity, but they will have little chance of running into each other if they have the same velocity. Impaction can be described by the following equation:¹

$$K_I = (C_c d_p^2 v \rho_p) / (18 \mu D_c)$$

Where:

K_I = Impaction parameter (dimensionless)

C_c = Cunningham correction factor (dimensionless)

d_p = Particle diameter, (microns)

v = Difference in velocity (cm/sec)

D_c = Diameter of droplet (cm)

μ = Gas viscosity, kg/m-sec

ρ_p = Particle density

Impaction
Equation

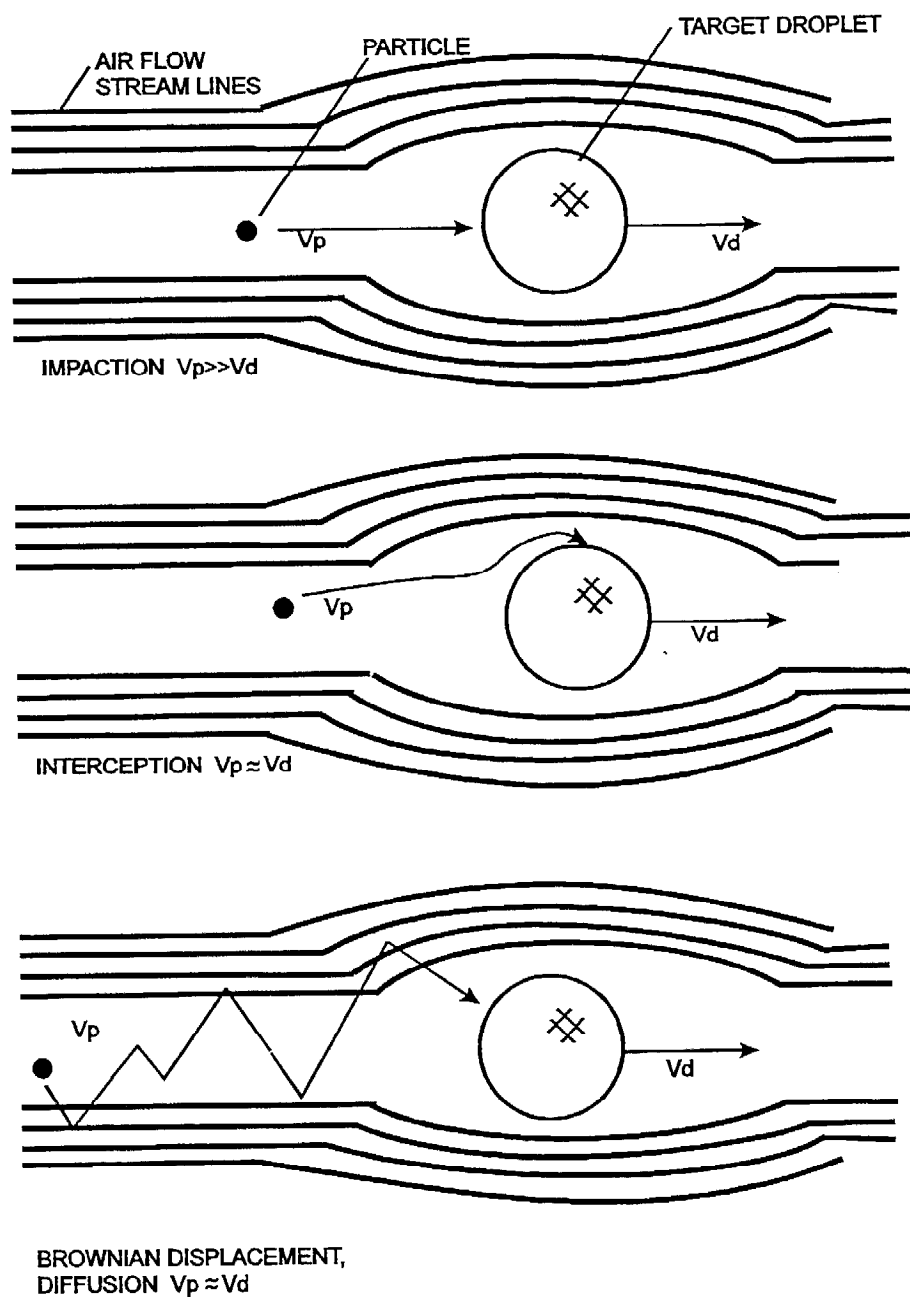


Figure 603.1 Main Particle
Collection Mechanisms

The larger the impaction parameter is in this calculation, the higher the efficiency of impaction.

603.2 INTERCEPTION

Interception occurs with particles that are smaller than those that are collected by impaction. Particles that have a smaller mass follow the gas stream lines around liquid droplets, but if the distance between the center of the particle and the surface of the droplet is less than the radius of the particle, the particle will hit the droplet and can be intercepted (Fig. 603.1). Interception between a particle and a droplet occurs at angles much less than 90°. Particles in the submicron range are mostly engulfed by droplets by interception. Interception in a scrubber can be maximized by fine sprays in a scrubber which produce a large number of small droplets.

603.3 BROWNIAN DISPLACEMENT

As with impaction, Brownian displacement is a important collection mechanism for scrubbers. A large portion of particulate matter is removed from a gas stream by Brownian displacement.

Extremely small particles will deflect from their direction of movement as a result of collisions with molecules of air. The transfer of kinetic energy from air molecules to the particles causes the particle's change in velocity and direction. Brownian displacement is an important collection mechanism for particles between 0.01 and 0.1 microns in diameter. Small particles are affected more by Brownian displacement, and the effect of Brownian displacement on large particles is negligible. Particles are captured by Brownian displacement when a random particle movement causes an impaction with a water droplet (Fig. 603.1).

Diffusion
Charging
and Field
Charging

The rate of diffusivity caused by Brownian displacement can be expressed by the following equation:¹

$$D_p = (C_c KT) / (3\pi\mu d_p)$$

where:

D_p = Diffusivity of particles (cm²/sec)

K = Boltzman constant (gm-cm²/sec²-°K)

T = Absolute temperature (°K)

C_c = Cunningham correction factor (dimensionless)

μ = Gas viscosity (kg/m-sec)

603.4 ELECTROSTATIC ATTRACTION

Most aerosols carry some electrical charge, which is constantly transferred between randomly colliding particles.¹ This process is known as diffusion charging. Unlike charges between particles cause the particles to attract each other. The charged particles can stick together and form a single particle with a higher mass, making it easier to remove. Diffusion charging is an important collection mechanism for particles that are less than 0.4 microns in diameter. A particle charged from diffusion charging can hold 1 to 200 charges, with each charge considered to be the smallest unit of charge, the electron.

Field charging is the charging of particles by the use of a strong electrical field. This is done in electrostatic precipitators and some scrubbers. Particle collection by means of field charging is important for particulates over 0.4 microns in diameter. These larger particles can hold up to 20,000 to 30,000 charges on each particle.

The forces created in an electric field can be thousands of times greater than gravity. The force between particles from electric fields is given by the following expression:

$$F_e = neE$$

where:

n = Number of charges

$e = 4.8 \times 10^{-10}$ (statcoulombs)

E = Electric field strength (kV/cm)

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

$$300 \text{ V} = 1 \text{ statvolt}$$

$$1 \text{ statvolt} = 1 \text{ statcoulomb/cm}$$

$$F_e = \text{Force (dyne)}$$

$$1 \text{ dyne} = 1 \text{ statcoulomb}^2/\text{cm}^2 = 1 \text{ (gm)cm/sec}^2$$

603.5 GRAVITATIONAL SETTLING

Some particles are removed in a scrubber by gravitational settling. Some particles have a large enough mass so that gravity can have an effect on the particles, pulling them down to the bottom of a scrubber into the scrubber liquor (the liquid in the scrubber). Table 603.1 shows the terminal settling velocities for a range of particle sizes.¹ Once the particle diameter gets below 10.0 microns, the effect of gravitation settling begins to become ineffective.

| Table 603.1 Particle Terminal Settling Velocities | |
|--|---------------------------------------|
| Particle diameter (microns) | Settling velocity (cm/sec) |
| 0.1 | 0.000087 |
| 1 | 0.0035 |
| 10 | 0.304 |
| 50 | 7.5 |
| 80 | 19.3 |

603.6 THERMOPHORESIS

Thermophoresis is a collection mechanism caused by relatively weak forces. Particle movement by thermophoresis is caused by thermal differences on two sides of a particle.¹ The gas molecules on the hot side of a particle will have higher kinetic energy than those on the cold side of a particle. Therefore, more energy will be transferred to a particle from collisions on the hot side. A particle will then tend to be moved in the direction of the cold side of a particle.

600 SCRUBBERS

603.7 DIFFUSIOPHORESIS

Diffusiophoresis is particle movement due to imbalances of kinetic energy being transmitted to a particle from collisions with molecules (usually air molecules) around it. It is primarily the same as Brownian displacement. The imbalance of kinetic energies from diffusiophoresis is caused by a larger concentration of molecules on one side than the other. The side of a particle that has more molecules will have more collisions, causing the particle to move in the direction with a lower concentration of particles. The effect on particle collection from diffusiophoresis can be increased from the evaporation or condensation of water. This could change the concentration of molecules around particles.

Particles that are engulfed by diffusion are extremely small, less than 0.5 microns in diameter. Particles of this size do not necessarily follow the gas stream lines. More particles can be collected by diffusion by maximizing the residence time of particles in a scrubber. Diffusion is more pronounced when there is a large temperature difference between the gas stream and the liquid. When there is a big difference in temperature, the liquid evaporates at a higher rate and creates areas of varying density. A particle will then diffuse from a more dense area to a less dense area.

603.8 OTHER COLLECTION MECHANISMS

Other mechanisms in which particles are wetted in a scrubber to a lesser degree include condensation and agglomeration. Condensation can occur if a gas is cooled below its dewpoint. If a particulate-laden gas stream is cooled below its dewpoint, the particulates will act as condensation nuclei. Particles are wetted from the condensation of water on their surface and can be more easily collected. Condensation works well for particulate-laden gas streams that are hot, since hot air can hold more water, and cooling will force more water to condense.

Agglomeration occurs when particles in the gas stream impact with each other and stick together, forming a single particle with a larger mass. Gravitational settling effects can then more easily remove the particle from the gas. A larger particle can also be wetted more easily by impaction.

Condensation
and
Agglomeration

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

604 LIQUID-TO-GAS RATIO

The amount of liquid used relative to the amount of gas flowing through a scrubber is an important parameter. The liquid flow rate is usually gauged in gallons per minute (gpm) and the gas flow rate is usually gauged in actual cubic feet per minute. The liquid-to-gas ratio is usually measured as the gallons per minute of scrubbing liquid used for every 1000 actual cubic feet per minute of gas (acfm). The word "actual" means the gas stream is not corrected for temperature and pressure from standard temperature and pressure (STP). The term "scfm" stands for standard cubic feet per minute and "standard" means the conditions have been corrected to STP conditions (14.7 psia and 32.0, 60.0, 68.0, or 70.0 degrees Fahrenheit). Forms of the equation of state can be used to calculate standard and actual conditions for ideal gases i.e.

$P_1 V_1 / T_1 = P_2 V_2 / T_2$. The gas flow portion of this ratio is usually evaluated at the scrubber outlet, since there are usually test ports for gas velocity available.⁹

Most scrubbers have liquid-to-gas ratios between 4 and 20. Increasing the liquid-to-gas ratio beyond 20 does not increase particle collection efficiency because of the droplet size distribution. If the liquid-to-gas ratio starts to get too large, a slight decrease in collection efficiency may begin to occur. If the liquid-to-gas ratio gets too low, a much higher adverse effect will occur. A low liquid-to-gas ratio will produce fewer target droplets for particles to impact. Parts of the gas stream could then pass through the scrubber without encountering a liquid droplet.

The liquid-to-gas ratio for gas absorption in a scrubber is higher than the best liquid-to-gas ratio necessary for particulate removal. If both absorption and particle removal is required, the liquid-to-gas ratio is usually set to provide maximum absorption efficiency.

605 TYPES OF WET SCRUBBER DESIGNS

All scrubbing systems must accomplish three major tasks in order to be efficient. Scrubbers must produce a large number of droplets or "targets" for collision with particulate matter. Secondly, the gas stream must be manipulated so that collisions between droplets and particles will be maximized. Then the

STP

600 SCRUBBERS

particle-laden droplets must be collected and removed from the gas stream. Scrubber designs can primarily be differentiated by the method used to produce droplets and droplet-particulate collisions.

Many types of scrubber designs have been developed, but most of the popular designs that have been used include spray chambers, spray towers, cyclonic scrubbers, wet dynamic/mechanically aided scrubbers, impingement plate scrubbers, packed bed scrubbers, froth scrubbers, wet ionizing scrubbers, ejector venturi scrubbers, gas ejector scrubbers and venturi scrubbers. These scrubbers will be discussed in their approximate order of increasing efficiency.

605.1 SPRAY CHAMBERS

Spray chambers are the simplest type of scrubbers. Spray chambers are used to remove very coarse dust from hot gas streams or for conditioning an exhaust stream.

When flue gas enters a spray chamber the velocity of the gas slows, since the chamber widens from the ducts carrying the flue gas. This helps increase the residence time of the flue gas in the spray chamber. Increasing the residence time in a spray chamber helps increase the capture efficiency of particulates.

The collection efficiency of spray chambers is low, but they also serve as gas coolers or humidifiers. The humidification provided by a spray chamber allows moisture to condense on particles and can increase collection efficiency. Collection efficiency can be improved by adding baffle plates inside the chamber to increase the area where wetted particles can impinge.

The water rates used for spray chambers is typically 3.0 to 8.0 gpm (gallons per minute) for every 1,000 cfm of gas.¹⁰

Spray chambers can use a co-current flow, counter flow or cross flow configuration between a liquid and a pollutant-laden gas stream. In the co-current flow configuration, where the gas and the liquid flow in the same direction, collisions caused by the relative velocity between the gas and the liquid are at a minimum.¹¹ This configuration is rarely used since it has the lowest efficiency. In a counter flow configuration the liquid and gas flow in the

opposite direction. In this design the relative velocity between the liquid and gas is maximized and the collection efficiency will be much higher. Spray nozzles for the liquid can be on the sides of the chamber. This design is called a cross-flow configuration, since the liquid and gas flow perpendicular to each other. The collection efficiency of the cross flow design is greater than the co-current flow design, but it is less than the collection efficiency acquired in the counter flow design.

Spray chambers are used in exhaust systems for light dust cleaning, electroplating, fume control, and preconditioning dust from acid phosphate fertilizers. They may also be used to clean up exhaust gases from the recovery furnaces in the kraft pulp manufacturing processes.¹¹

605.2 SPRAY TOWERS

Spray towers (also called gravity spray towers) are another type of spray scrubber that works similarly to a spray chamber. Liquid droplets that are produced at the top of the tower by spray nozzles or atomizers, fall with the aid of gravity to the bottom of the tower, while the gas stream containing dust particles rises up the column (Fig. 605.1). Most spray tower designs are equipped with mist eliminators and gas distribution plates. Mist eliminators help remove water that is entrained in the gas stream. Mist eliminators are at the top of spray towers above the spray nozzles. Gas distributor plates help distribute the gas flow uniformly so the spray of the liquid will wash the entire gas flow. A gas distributor plate may also serve as a support for packing. A bed of packing 6.0 to 12.0 in. in depth may be put in the bottom of the tower to increase collection efficiency. Packing increases the area that wetted particulates can impinge.

The velocity of the falling liquid droplets must be greater than the velocity of the pollutant-laden gas or liquid entrainment and carryover could occur. In most spray tower applications the gas flow velocity is limited to 2.0 to 5.0 ft/sec. If the velocity of the gas is higher, a mist eliminator must be used at the top of the tower.

In a spray tower, the efficiency is improved by the increased difference in relative velocity between the falling liquid and the gas rising up the tower. The higher the relative velocity is, the higher the collection efficiency. The

600 SCRUBBERS

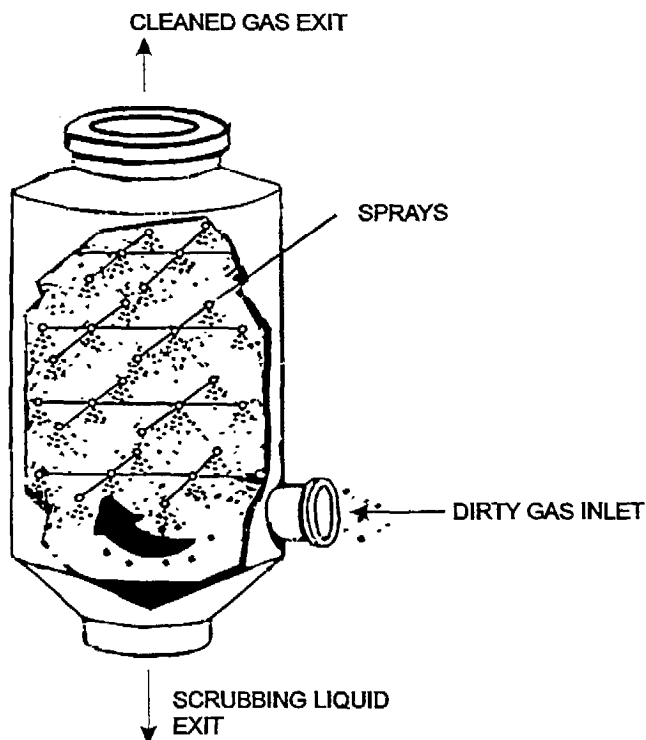


Figure 605.1 Spray Tower

collection efficiency is also higher with smaller droplet sizes. In gravity and spray towers these conditions are contradictory. Smaller droplets tend to float more in the gases flowing up a tower; therefore, the relative velocity between the liquid and the gas is lower. The range for droplet size to maximize collection efficiency in spray towers is 500 to 1000 microns.¹¹

Spray towers have a low pressure drop of 1.0 in. of water, not including mist eliminators and gas distributors in the device. They typically use 5.0 to 20.0 gallons of liquid for every 1000 cfm of gas they clean.¹¹ As with spray chambers, the collection efficiency of spray towers is low. Most spray tower applications are limited to controlling particulates that are 10 microns or greater in diameter. Another disadvantage of spray towers is that they have

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

large space requirements. On the other hand, they are good gas coolers and the liquid used for the spray can have a high solids content. Once liquid is sprayed in the tower to collect particulates, it can be recirculated back to the spray tower and sprayed again. The spray droplet size in spray towers is relatively large, reducing the chances of clogging of the spray nozzles from solids in the liquid.

605.3 WET DYNAMIC/MECHANICALLY-AIDED SCRUBBERS

Some mechanical scrubbers typically use hydraulically atomized sprays which are introduced to the inlets of fans, or paddle wheels (Fig. 605.2). The collection mechanism is mainly impaction of particulates on water droplets generated by rotating blades of the fan and the inlet liquid spray. The liquid spray keeps the blades wet and continually washes away dust particles. The fan also serves as a method of increasing the gas stream velocity, thus increasing the difference in velocity between the particle-laden gas and liquid droplets.

The centrifugal fan wet scrubber is limited to controlling particles over one micron in diameter. This scrubber has a limited collection efficiency because of low differences in velocity between the water droplets and gas stream, since they are moving co-currently. Most mechanical scrubbers can reach a collection efficiency of over 95% for particulates over 5.0 microns.

The mechanical, centrifugal scrubber shown in Figure 605.2 and similar designs are good for controlling nonabrasive particulates. Abrasive particles will rapidly wear down the fans. These scrubber designs have been used to control particulates from mines and may be used to control large-sized, nonabrasive particulates from other processes.

Figure 605.3 illustrates a vertical spray rotor scrubber. In this type of mechanical scrubber design, the water spray is generated by a rotating mechanical device. There are also other designs that use partially submerged rotor devices to atomize scrubbing liquid. Liquid is also atomized at the scrubber walls. Impaction is created by the rapidly moving water droplets and the motion of the gas stream.

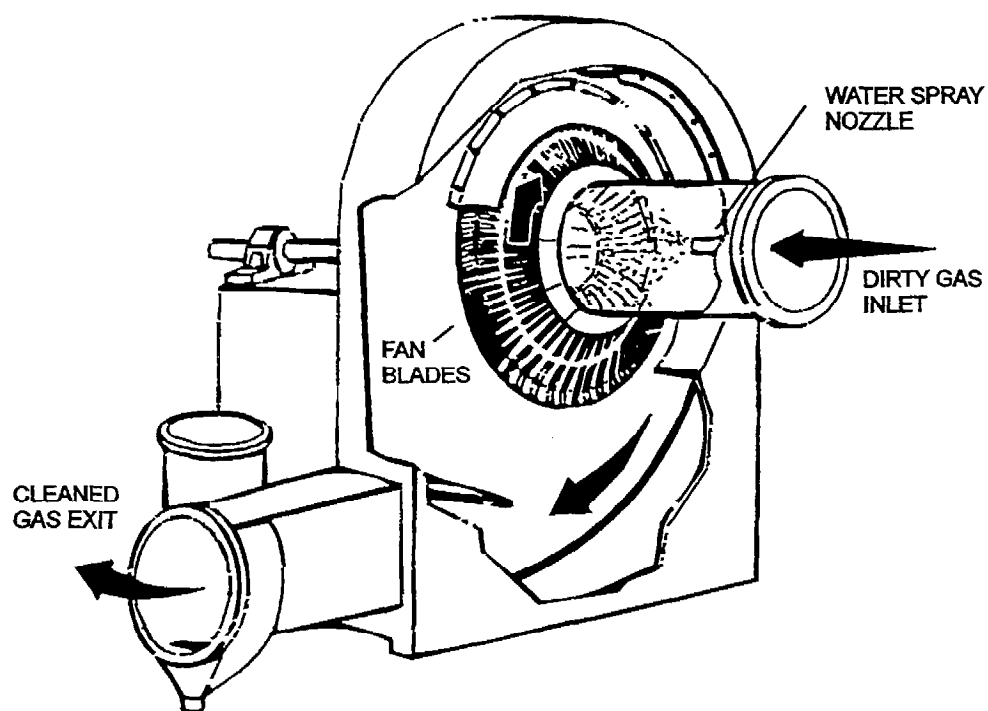
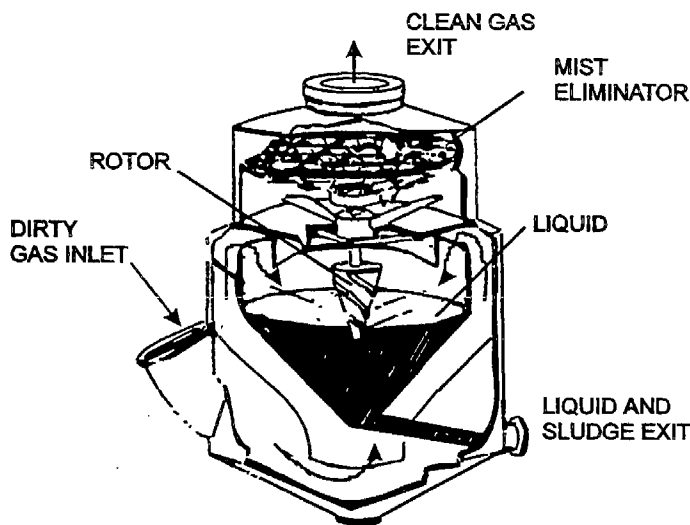


Figure 605.2 Wet Dynamic/
Mechanical Scrubber



**Figure 605.3 Vertical Spray
Rotor Scrubber**

The rotor-type scrubbers have low liquid requirements and can handle a high dust loading. Rotor-type scrubbers are also not prone to plugging since they have no spray nozzles. On the other hand, the rotor elements are susceptible to wear, especially with abrasive dusts.

605.4 TRAY TOWER SCRUBBERS

Tray tower scrubbers use impingement devices such as plates, trays, or baffles to clean particulates from an air stream. Other names of scrubber designs that use these devices include tray tower scrubbers and impingement tray scrubbers. In impingement scrubbers, gases are accelerated into and passed through plates that are covered with openings. As the pollutant-laden gas passes through the plate, it is washed by a scrubbing liquid that flows on top of the plate. The principle means of collection of particles is impaction.

Different types of tray designs are used in impingement plate scrubbers. The simplest trays may simply have holes or perforated plates for particle and droplet impaction. Some plate designs may be equipped with bubble caps, movable discs, or even adjustable trays. The plates are made of metals or plastics such as polypropylene or PVC. Figure 605.4 shows a design where

Tray Materials

600 SCRUBBERS

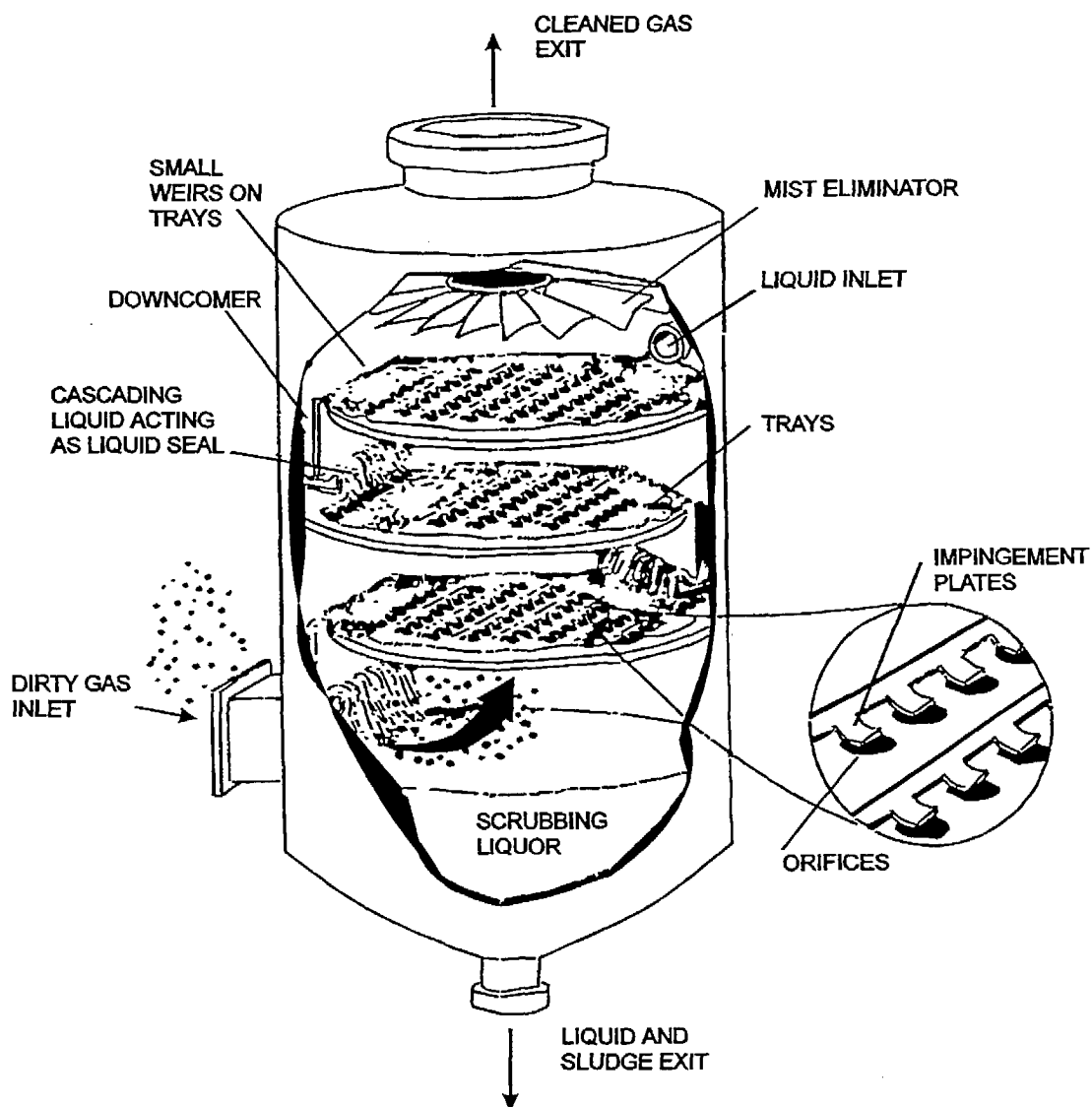


Figure 605.4 Tray Tower Scrubber

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

small baffles are mounted over orifices on each tray. In this impingement tray scrubber the orifices are approximately 3/16 inches in diameter and a layer of water between 1.0 to 1.5 inches is kept on each tray.¹ The level of the water on each tray is set by weirs.

Scrubbing liquid initially enters a tray scrubber near the top and flows through the device by gravity. Liquid that does not flow through the holes in the tray flows over a weir and down a downcomer to the next tray. The liquid continues to flow down through downcomers or the holes in the tray until it gets to the bottom of the scrubber. The pollutant-laden gas passes up through the holes in each tray until it reaches the exit at the top of the scrubber. The downcomers are designed so that the liquid cascading down the downcomer forms a liquid seal, preventing the gas stream from going up a downcomer. Scrubbing liquid takes the path of least resistance and it is easier for liquid to pass through the holes on a tray since there is a higher column of liquid in each downcomer than on each tray.

As the gas stream flows through the holes in a tray, its velocity increases. The increase in velocity is due to the small area that the gas stream is forced through. The gas stream atomizes the liquid lying above the holes on the tray. This helps produce more droplet targets for particles to impact. Some wetted particles are removed from the gas stream by mist eliminators near the top of the scrubber. The space between the mist eliminator and the upper tray are maximized in many designs in order to allow gravity to settle particle laden droplets into the scrubbing liquid.

The trays in impingement scrubbers are important in the efficient operation of the devices. The trays must be very flat and they must be put into the scrubber so they are level. If trays are bowed, the depth of the scrubbing liquid on the tray will not be uniform. The gas stream will then tend to flow through areas of the plate with the least scrubbing liquid since the gas takes the path of least resistance. Orifices through which excessive portions of the gas stream flow will not be as effective at liquid and droplet impaction. An excessive flow of gas through the orifices creates fewer droplet targets for particles to impact.

Another possible problem with impingement scrubbers is plugging of the holes in the trays. Solids suspended within the scrubbing liquid can accumulate in the small holes in the trays. This could cause increased pressure drop and decreased collection efficiency. If plugging occurs, the equipment may have to

600 SCRUBBERS

be taken out of service and the holes may have to be drilled or rodded out. The solids content of the scrubbing liquid used for impingement scrubbers must be carefully monitored to avoid plugging.

Impactor and impingement scrubbers can be used for a wide variety of scrubbing applications. They have been used for boilers that produce a large sized char, and for lime kilns. These types of scrubbers also have good gas absorption properties. They have also been used to remove halogenated gases from air streams.

Most impingement scrubbers use a relatively small amount of liquid and have a relatively low amount of pressure drop that varies between 3.0 to 8.0 in. of water column. Each tray in a impingement scrubber may add 2.0 to 3.0 in. of water column to the pressure drop. Additional trays help improve collection efficiency since there are more opportunities to capture particles. The liquid rates for impingement scrubbers usually vary between 2.0 and 10.0 gal of liquid for every 1000 cfm of air.¹²

Impactor and impingement scrubbers are not efficient for the removal of submicron particulate, but they can attain over 98% collection efficiency from the larger size char from bark (wood waste) boilers.¹² The relatively low collection efficiency from impingement scrubbers is due to the low velocity of gases through the holes in the trays. Most tray and impingement scrubber designs are made to control particulates over one micron in diameter.

605.4.1 Sieve Tray Scrubbers

Sieve tray scrubbers are tray scrubbers that have larger sized orifices in each tray. The larger sized orifices makes these scrubbers less prone to plugging. On the other hand, the gas stream velocities in the orifices of sieve tray scrubbers are lower, lowering collection efficiency.

605.4.2 Catenary Grid Scrubbers

Catenary Grid Scrubbers (a registered trademark of Otto York Co.) use pairs of trays (grids) with a catenary (curve) shape. Liquid is introduced above the top trays and flows through the scrubber without the need of downcomers. As with

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

other tray scrubbers, contact between the scrubbing liquid and pollutant occur on top of the grid pairs or trays. Catenary Grid Scrubbers work well for particulate control and gas absorption.

Catenary Grid Scrubbers operate with very low pressure drops. Each stage (grid pair) in the scrubber has a pressure drop of approximately 1 inch of water gage per stage. A typical Catenary Grid Scrubber under normal operation will have a total pressure drop up to 5 inches of water and is equipped with one to three stages.⁷

Gas flow velocities in Catenary Grid Scrubbers range between 12 to over 33 ft/sec. The liquid to gas ratio is usually 0.5gal/1000acf or higher.⁷

605.5 PACKED BED SCRUBBERS

Some scrubbers may have beds of packing material primarily for gas absorption. The packing material serves as a way of providing a very large wetted surface area in the scrubber. A large wetted surface area is necessary to maximize contact between the liquid and gas for high absorption efficiency or particle collection. Gas absorption within a scrubber can also be used as a method of odor control. For particle collection, the scrubbing liquid wets, washes, and dissolves particles from the bed.

There are many different types of packing materials available. The most common types include tellerettes, raschig rings, pall rings, berl saddles, intalox saddles, marbles, and others (Fig. 303.3). Smaller diameter packing tends to give a higher collection efficiency than larger sized packing at a given gas velocity. For two given equal volumes, one filled with large-sized packing and another filled with small-sized packing, the volume with the small sized packing will have a larger surface area.

There are a number of different scrubber designs that use packing material. A packed scrubber can be a counter-flow or cross-flow configuration. Furthermore, the bed of packing material in the scrubber can be a fixed bed, flooded bed, or a moving bed.

Main Types of Packing

600 SCRUBBERS

605.5.1 Cross-flow and Counter-flow Arrangements

In a packed bed scrubber operating under a cross-flow configuration, liquid is typically put into the top, allowing the pull gravity to wet the packing while the gas stream flows horizontally through the bed of packing (Fig. 605.5). Sprays may also be put at the entrance of the dirty gas to the packing, especially when particulates are being controlled, to wash particles from the packing and prevent plugging. Sprays at the entrance can also serve to condition the gas stream. The leading edge of the packing is typically angled seven to ten degrees (depending on the velocity of the gas) in the direction of the gas flow to ensure complete wetting of the face packing by the liquid cascading from the top of the scrubber. The back edge of the packing may be left dry and free of scrubbing liquid to provide mist elimination.

Cross-flow packed scrubbers generally operate with a relatively low pressure drop and low liquid requirements. The pressure drop is typically between 0.2 and 0.5 inches of water per foot of packing and the liquid requirements are generally between 1 to 4 gallons per 1000 ft³ of gas.¹¹ The collection efficiency

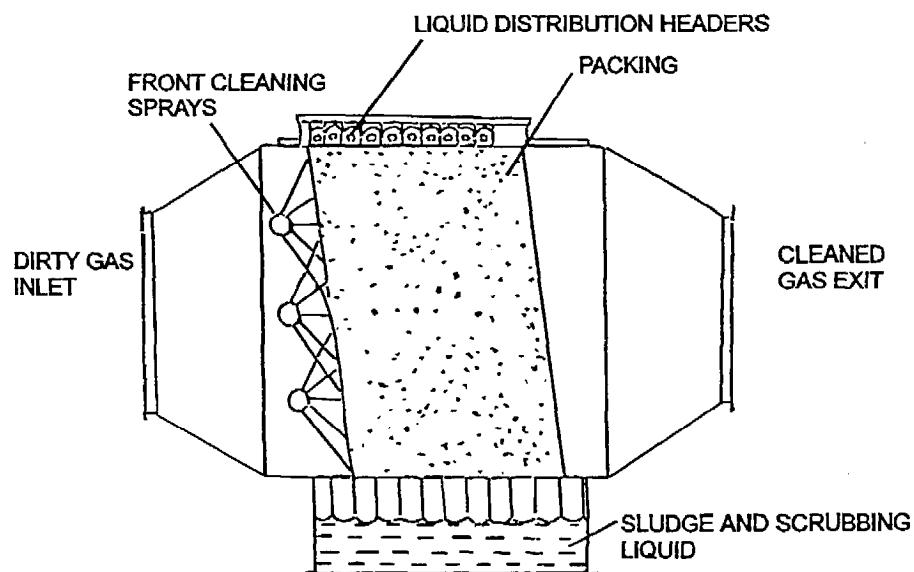


Figure 605.5 Cross-Flow Scrubber

600 SCRUBBERS

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for particles in these scrubbers is low; it is typically 90% for particles over 2 microns in diameter. As mentioned earlier, these scrubbers are primarily gas absorbers. The dust loading capacity is typically 5 grains per cubic foot.¹¹

The counter-flow arrangement is the most common scrubber design for packed scrubbers (Fig. 605.6, 605.7, 605.8). A flow of liquid is typically introduced in the scrubber below the mist eliminator and flows through the packing by gravity while the gas stream flows up through the packing.

Counter-flow packed scrubbers generally work best with a pressure drop between 0.5 and 1.0 in. per foot of packing.¹¹ Higher pressure drops may result in excessive liquid entrainment. Liquid rates may vary between 10 to 20 gallons per 1000 ft³ of gas.

Packed scrubbers have also been built with a co-current design where the gas and scrubbing liquid flow the same direction. This is the least efficient arrangement, but the co-current design reduces the possibility of clogging. A co-current design uses less scrubbing liquid; its liquid requirements are generally between 7 to 15 gallons per 1000 ft³ of gas. The pressure drop for a co-current arrangement is between 1 and 4 in. per foot of packing.¹¹

605.5.2 Fixed Packed Bed Scrubbers

Packed bed scrubbers with a stationary bed are mainly used for gas absorption and odor control. Some other names for the types of scrubbers fitting this category include vertical packed bed scrubbers or packed towers.

Vertical packed bed scrubbers or packed towers may have a series of packed beds (Fig. 605.6). As the scrubbing liquid flows down through the scrubber, the liquid is redistributed to make sure all of the packing is continually wetted. Redistribution is very important for the absorption of gases.

These types of scrubbing systems have a very limited capability for particulate removal for particles that are less than 3 microns in diameter. Gas and liquid velocities are low so impaction is reduced. Furthermore, plugging of the bed from particles can be a problem with fixed bed packed scrubbers.

**Primarily Gas
Absorbers**

600 SCRUBBERS

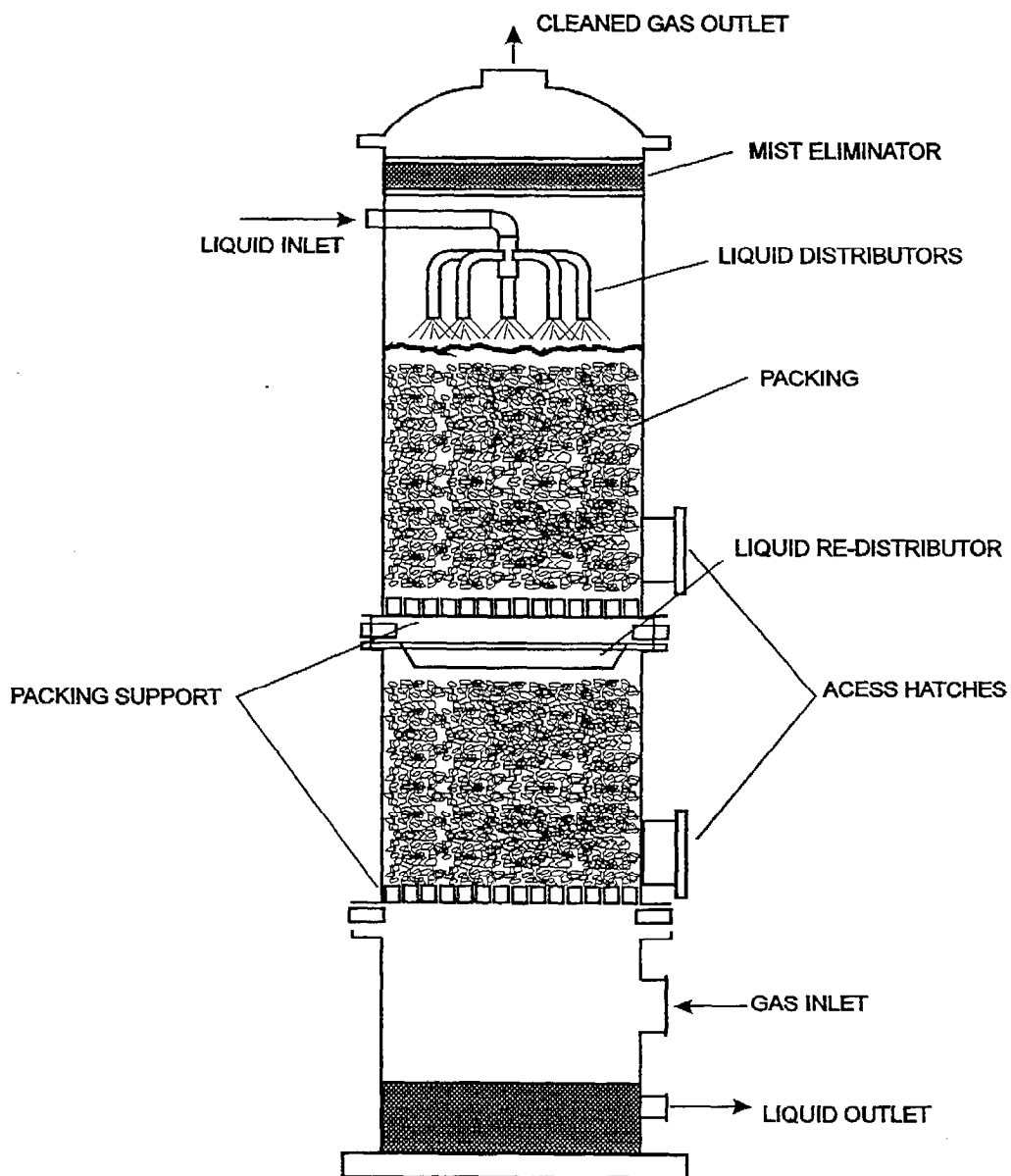


Figure 605.6 Packed Column

600 SCRUBBERS

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605.5.3 Moving Bed Scrubbers

Moving bed scrubbers use a moving bed of packing for particulate removal or gas absorption. The type of packing material is similar to ping pong balls. It is spherical in shape and the packing is made of a low density material. The packing material is put between two open supporting trays and the space between the trays is 40 to 50% filled with the packing material (Fig. 605.7).

As with most scrubbing applications, the pollutant-laden gas enters the bottom of the scrubber while liquid is sprayed from the top. The motion of the gas stream, liquid and random collisions with other pieces of "ping pong" packing causes the packing to move randomly. The gas and the packing material

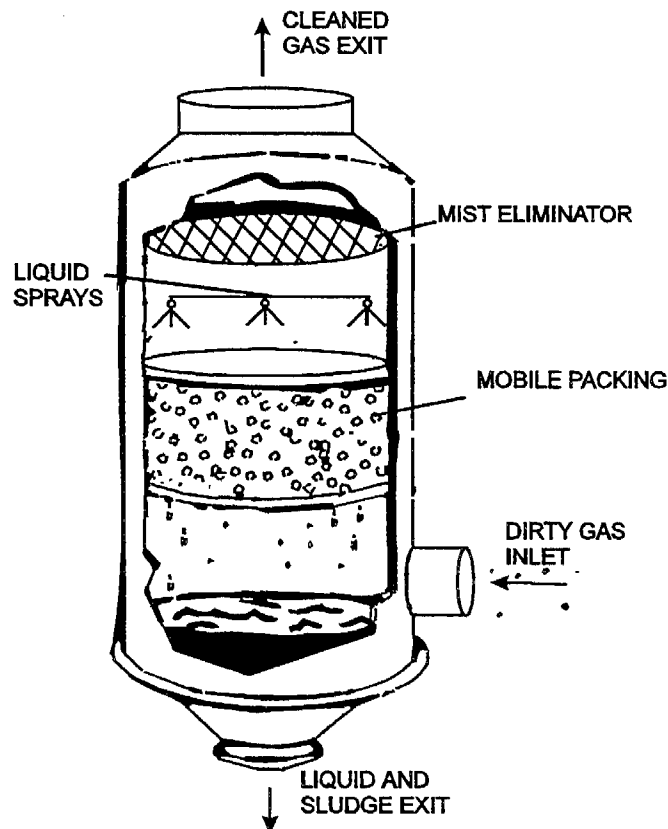


Figure 605.7 Moving Bed Scrubber

atomize the liquid, providing target water droplets for particles. The continuous movement of the bed and the water sprays also helps prevent the buildup of solids on the packing, preventing plugging of the packed bed.

Applications of moving bed scrubbers include the removal of particulates and SO₂ from the flue gas of combustion processes.

605.5.4 Flooded Bed Scrubbers

The flooded bed scrubber uses a counter-flow arrangement with a bed of marble-like packing (Fig. 605.8). In this scrubber design, the particulate-laden gas stream enters the side of the scrubber and flows through the bed of packing, which is flooded with scrubbing liquid. As particles flow through the bed they impact droplets created from the liquid that were atomized by the gas stream.

Marble-Like Packing with Gentle Rubbing Action

The smaller sized marble-like packing in the flooded bed scrubber is heavier than the packing used in a moving bed scrubber, but the individual packings have a gentle rubbing action that helps clean particulates from the packing and prevent plugging. A 6.0 in. turbulent layer of liquid is formed on top of the packing as the gas flows through it. Entrained mists are removed by the mist eliminator and the cleaned gas stream exits at the top of the scrubber.

Flooded bed scrubbers have a collection efficiency of 99% for particles of 2.0 microns or larger. The pressure drop varies between 4.0 to 6.0 in. of water column and the liquid requirements are 2.0 to 2.5 gallons for every 1000 ft³ of gas. A flooded bed scrubber can handle a grain loading up to 40 grains per ft³ of gas.¹¹

Applications of flooded bed scrubbers include the control of acid gases, carbon black particulates, ceramic grit, chlorine tail gas, cupola gas and ferrite dusts.¹¹

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

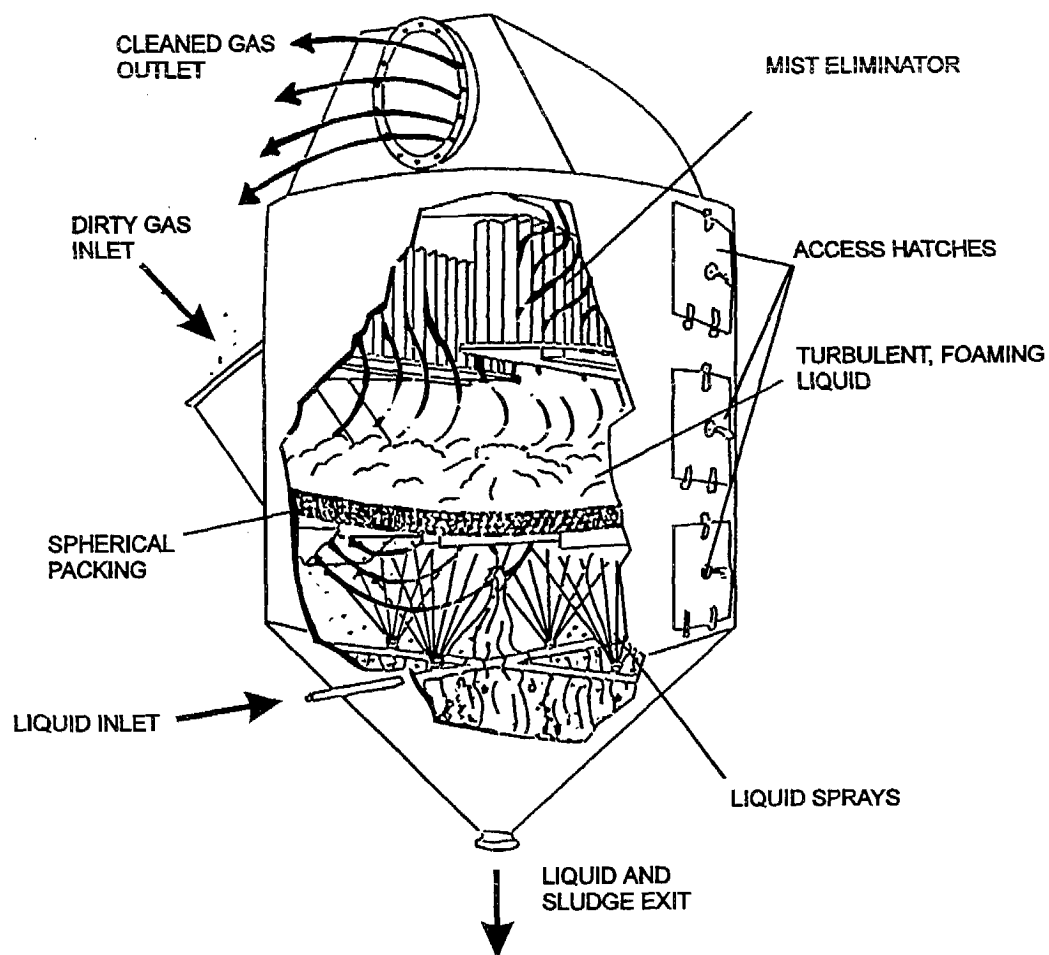


Figure 605.8 Flooded Bed Scrubber

600 SCRUBBERS

605.6 WET IONIZING® SCRUBBERS

This type of scrubber primarily uses a electrostatic attraction to remove particulates from a gas stream similar to an electrostatic precipitator, but it also employs wet collection (Fig. 605.9). When the gas stream enters the device, it passes through a short ionization section which imparts an electric charge to particles in the air stream. The ionization section is composed of a series of high voltage electrodes and small plates that are grounded. Unlike an electrostatic precipitator, the particles do not collect on the plates. The ionizer operates with a secondary voltage between 20,000 to 30,000 volts D.C.¹

After charged particles pass through the ionization section they are removed by the scrubber cross-flow section. The cross-flow scrubber consists of a bed of packing with spray nozzles situated above the packing, spraying a constant flow of water. The ionized particles enter the scrubber perpendicular to the water flow. Tellerettes are usually the type of packing used in the wet ionizing scrubber.

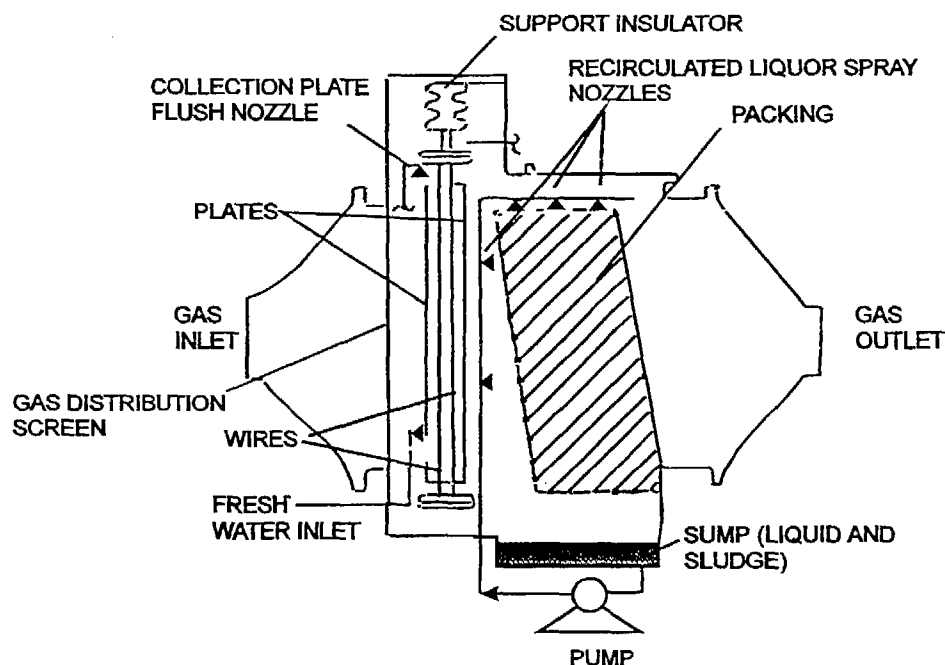


Figure 605.9 Wet Ionizing Scrubber

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

Water is a polar molecule, so when the charged particles come near the water-covered packing, the particles are attracted to the water and captured. The water molecules have a positive side and a negative side and particles are attracted to the side of opposite charge.

Collection efficiency may be increased by applying more than one wet ionizing scrubber stage on a gas stream.

605.7 FROTH SCRUBBERS

Froth scrubbers (Dynawave®) are a new type of scrubber design where scrubbing liquid is injected into a gas stream so that the momentum of the liquid and gas are balanced, creating a highly turbulent froth zone.¹ Particle impaction and gas absorption occur within sheets of liquid with the froth. Froth scrubbers can be used for particulate control or gas absorption.

The two main types of froth scrubbers include reverse jet and froth tower scrubbers. In the reverse jet device, a stream of liquid is injected upwards into a downward flowing gas stream. The froth tower scrubber has a tower containing baffles. Liquid descends within the tower and the gas flows up the tower. Liquid flow rates and the cross-sectional area of the gas flow through the baffles are maintained so froth layers can at least be created on the upper baffles.

**Two Types:
Reverse
Jet and Froth
Tower**

605.8 GAS-ATOMIZED SCRUBBERS

The main gas atomized scrubbers include venturi and rod deck scrubbers. Gas atomized scrubbers create a fine mist of liquid by shearing the scrubbing liquid with a rapidly moving gas stream.

605.8.1 Venturi Scrubbers

Venturi scrubbers are one of the most efficient wet collection devices. They can remove more than half the particulates in a waste stream that are in the submicron level (particulates with a diameter less than 1.0 microns).¹²

600 SCRUBBERS

Venturi scrubbers are named for the special "venturi" device that a particle laden gas stream is forced through. A venturi is a device similar to two cones joined at their narrow end. The narrowest portion of the device is called the throat. The part of the venturi where the dirty gas stream enters is called the converging section and the part where the gas stream exits the venturi is the diverging section. The inlet portion of a venturi is generally steeper and shorter than the exit portion (Fig. 605.10).

As the dirty gas enters the venturi the area of the venturi decreases and the velocity of the gas increases. This can be illustrated by the following expression:

$$Q = VA$$

where:

Q = Volume flow rate (ft³/sec)

V = Velocity (ft/sec)

A = Area of duct (ft²)

The equation shows that as the area of a duct decreases with a constant volume flow rate, the velocity will increase.

Scrubbing liquid is constantly injected into a venturi ahead of the throat. The liquid is sheared into a large number of small, fine droplets from the forces of the rapidly moving gas stream. This produces a large number of "targets" for particles to hit (Fig. 605.11). A high collection efficiency is also attained in a venturi scrubber because there is a large difference in velocity between the particles in the gas stream and the water droplets. As the gas stream enters the throat, it may reach velocities up to 250 miles/hour. Because of the high velocities reached in a venturi, the residence time of the gas stream may only be 0.001 to 0.005 seconds.¹ Most of the particle collection occurs during this time.

As the gas stream exits the throat of the venturi, impaction between particles and droplets decreases. The velocity of the water droplets increases, so the difference in velocity between the water droplets and the particles in the gas stream is lower.

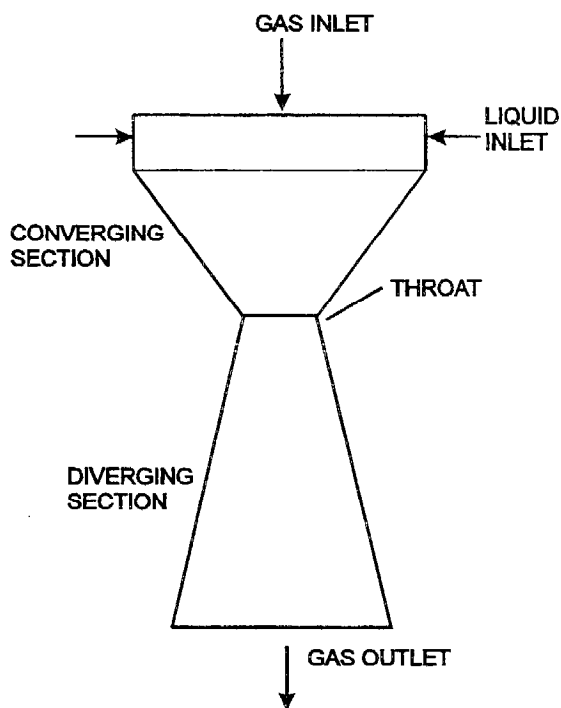


Figure 605.10 Venturi

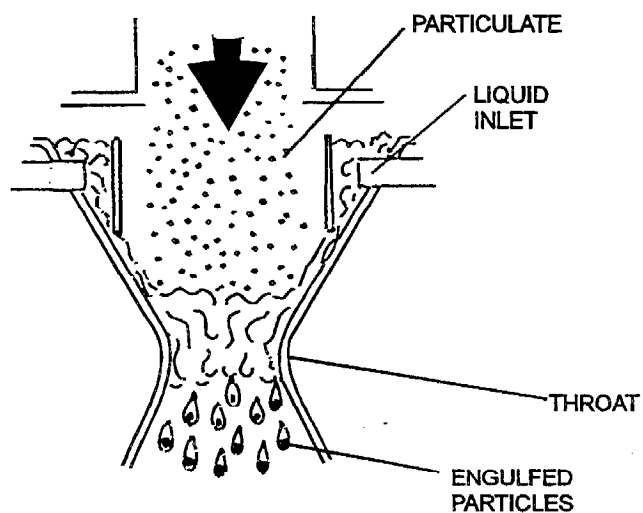


Figure 605.11 Impaction of Particles
and Target Droplets in Venturi

600 SCRUBBERS

Methods of Liquid Injection

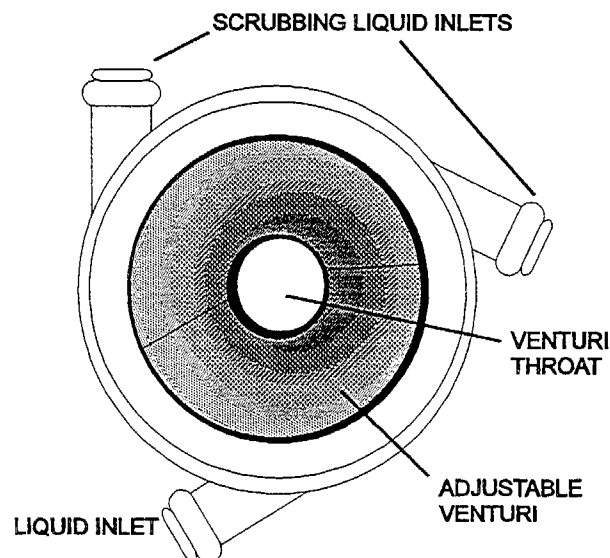
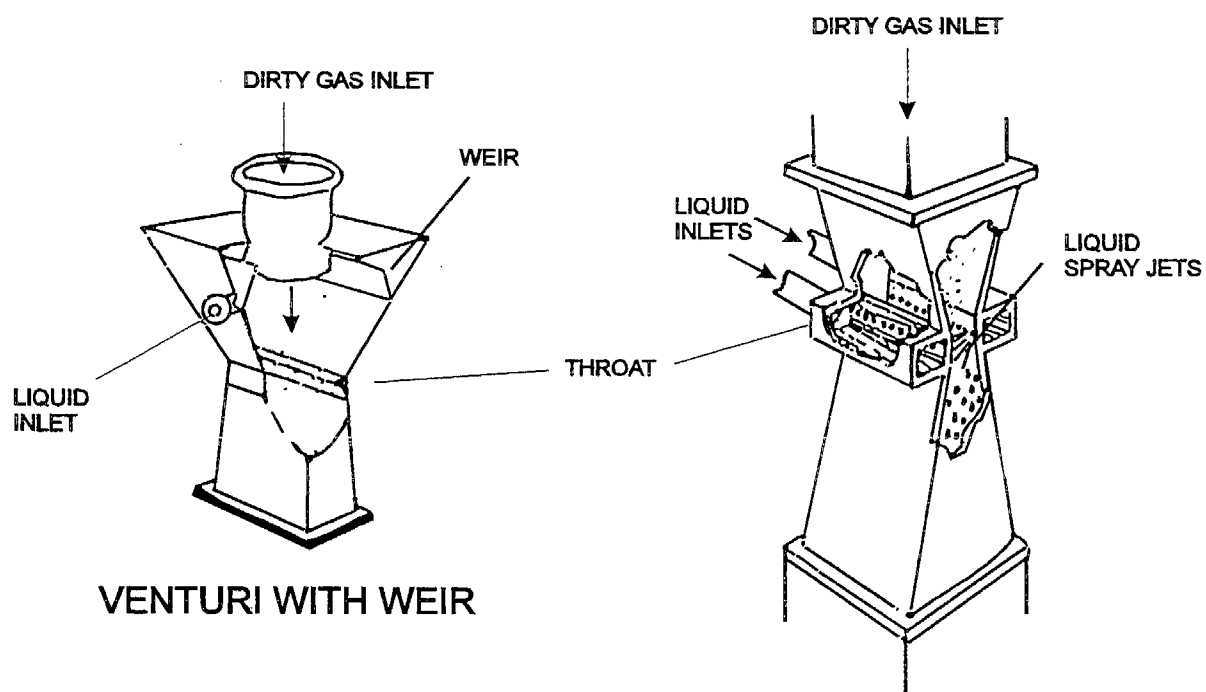
When the gas stream flows through the diverging portion of a venturi, it expands and the velocity decreases. After the gas stream leaves the venturi it enters a demister vessel so the particle-containing droplets can be removed.

Various venturi scrubbers inject the scrubbing liquid in different parts of the venturi and in different ways (Fig. 605.12). The scrubbing liquid may be injected right at the throat. Some designs may have the liquid injected further back at the entrance to the venturi. Scrubbing liquid may be injected perpendicular to the gas flow, against the direction of the gas flow or at another angle relative to the gas flow. In another variation, scrubbing liquid is fed to a venturi by an orifice plate. The scrubbing liquid may be fed to a venturi by weirs or by hydraulically or pneumatically atomized sprays. Atomized sprays can help produce a larger number of fine droplets to improve collection. Scrubbing liquid may also be sprayed into a venturi tangentially, producing a vortex-type motion of liquid similar to a "dentist's sink" (Fig. 605.12). The tangential spray and weir fed venturis have advantages in that a solids buildup near the throat entrance (also called the approach) is reduced.

Liquid Requirements

Venturi scrubbers typically require between 4 and 100 gal of scrubbing liquid for every 1000 acf (actual cubic feet) of air.¹² Spray-augmented venturi scrubbers use less water than hydraulically atomized venturi scrubbers, but hydraulically atomized venturi scrubbers are less prone to plugging of the nozzles. Liquid velocities for the tangential spray venturis is between 6 to 8 ft/sec.¹²

Some venturi scrubbers may be equipped with adjustable throats. Adjustable throats may be necessary for a scrubber system when variations in industrial processes create varying gas flow rates. If the throat of a venturi is adjustable, the velocity of the gas stream can be controlled with the throat adjustment. The simplest throat adjustment mechanism is simply a metal plate that extends across the throat from one side of the venturi. Dampers are often used to control the throat diameter. Other designs may be equipped with wedges, conical plugs, discs or other devices.¹² Manufacturers usually supply curves with their scrubbers showing throat velocity as a function of pressure drop and removal efficiency for different particle sizes, so the desired throat width can be attained. Most throat widths vary between an inch to over a foot, depending on the size and capacity of a venturi scrubber. Some venturis may have a rectangularly shaped throat, converging section and diverging section.



"DENTIST SINK" VENTURI

Figure 605.12 Venturi Scrubber Liquid Feeds

If the throat on an annular type (round-shaped duct) venturi is much over a foot in diameter, a void without scrubbing liquid can be formed. This could allow particles to flow through the venturi without coming into contact with any liquid droplets. An additional central sprayer must be used to keep a uniform distribution of fine droplets in the throat. The throats on rectangular venturis are limited to a width of 18 inches or they will also form voids without droplets.¹²

Since energy is lost in a venturi, an excess of energy in the form of velocity pressure must be added to the gas stream to account for the losses in the venturi nozzle. The main way of acquiring a high efficiency in a venturi scrubber is maximizing the density and uniform concentration of fine droplets. A high density of droplets increases the chances of collisions between liquid droplets and particles.

Once the gas stream passes through the venturi, particle-containing droplets must be removed. A cyclonic demister vessel may be used to accomplish droplet removal. A cyclonic motion is imparted on the gas stream to remove droplets. Systems use a variety of demisters for droplet removal. The most common demisters include wire mesh designs and chevrons (see mist eliminator section). Liquid droplets impinge on the sides of the demister vessel from the cyclonic motion. In other demisters droplets will also impinge on the surface of the demister. Droplets will then flow or fall to the bottom of the demister vessel due to gravity. The scrubber liquor, containing collected particles, is then discharged from the bottom of the demister vessel. Additional water sprays may be used to keep solids from clogging a demister.

In general, in a scrubber the higher the pressure drop that is designed in the system, the higher the collection efficiency that can be attained. Increasing the pressure drop across the control device increases the turbulence, which increases the collection efficiency at the expense of operating costs. Venturi scrubbers generally operate with pressure drops of 10 to 20 inches of water or more. The Hesketh equation can be used to predict pressure drop in a venturi scrubber.⁷

$$\Delta P = (V_t^2 \rho_g A^{0.133} L^{0.78}) / 1270$$

where:

ΔP = Venturi scrubber pressure drop (inches of water gage)

Equation for
Pressure Drop
in Venturi

600 SCRUBBERS

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V_t = Throat velocity (ft/sec)

ρ_g = Density of gas at throat (lbm/ft³)

A = Throat area (ft²)

L = Liquid-to-gas ratio (gal/1000 acf)

By extending the length of the diverging section of the venturi, the collection efficiency can be improved. The diverging section of venturi scrubbers operating above 40.0 in. of water column should be at least four times the throat inside diameter.¹² Increasing the length of the diverging section gives droplets more time to contact particles. The gas stream is inside the throat of a venturi for a very short period of time, allowing only a short period for droplets to contact particles.

605.8.2 Rod Deck Scrubbers

As with venturi scrubbers, rod deck scrubbers, also called venturi rod scrubbers, use a high velocity gas stream to atomize liquid droplets. Instead of a venturi, closely spaced rods are used to accelerate the gas stream (Fig. 605.13). Liquid is supplied to the rods by spray nozzles located above the rod deck. The spaces

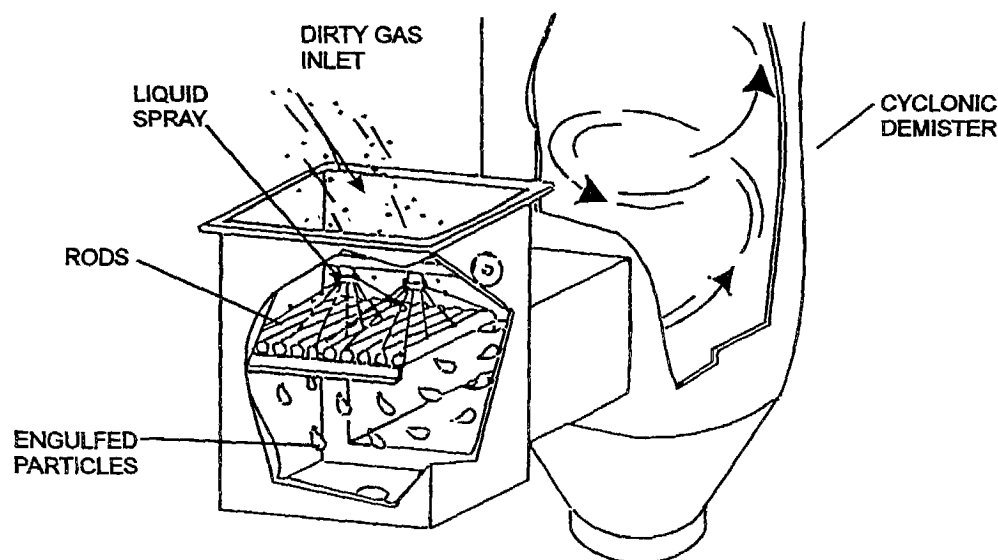


Figure 605.13 Rod Deck Scrubber

600 SCRUBBERS

between the rods on the deck may be adjusted on some units to control static pressure drop across the scrubber. Higher static pressure drops will tend to increase efficiency of particulate collection. Multiple sets of rod decks may also be used to increase collection efficiency.

605.8.3 Collision Scrubbers

In the collision scrubber design, the gas stream is split into two separate gas streams before being run through two separate venturis. As with venturi scrubbers, particles going through the venturis are wetted by scrubbing liquid. The two venturis are situated so the exiting gas streams with particle laden droplets collide with each other. Since the two streams are going in opposite directions, a large difference in relative velocity between the particles is created. The collision between the two gas streams creates another opportunity to collect particles with droplets.

605.8.4 Orifice Scrubbers

In an orifice scrubber, the gas stream is initially forced through a pool of scrubbing liquid (Fig. 605.14). Since a particle-laden gas stream only has one direction it can flow through the scrubber, it flows through a partially submerged orifice.

As the gas stream flows through the orifice, it atomizes some of the liquid. The atomization produces small droplets which can be targets for small particles. Large particles will be collected from impacting the surface of the scrubbing liquid.

After the gas stream exits the orifice, particle-laden droplets are removed by baffles. Droplets impinge on the baffles and the scrubbing liquid drips down to the bottom of the scrubber. Over time, sludge from the collection of particles may accumulate in the bottom of the scrubber and have to be periodically removed.

Orifice scrubbers tend to be good for processes that produce sticky particulates. They have a medium collection efficiency (about 50%) for particles that are one micron in diameter.⁹

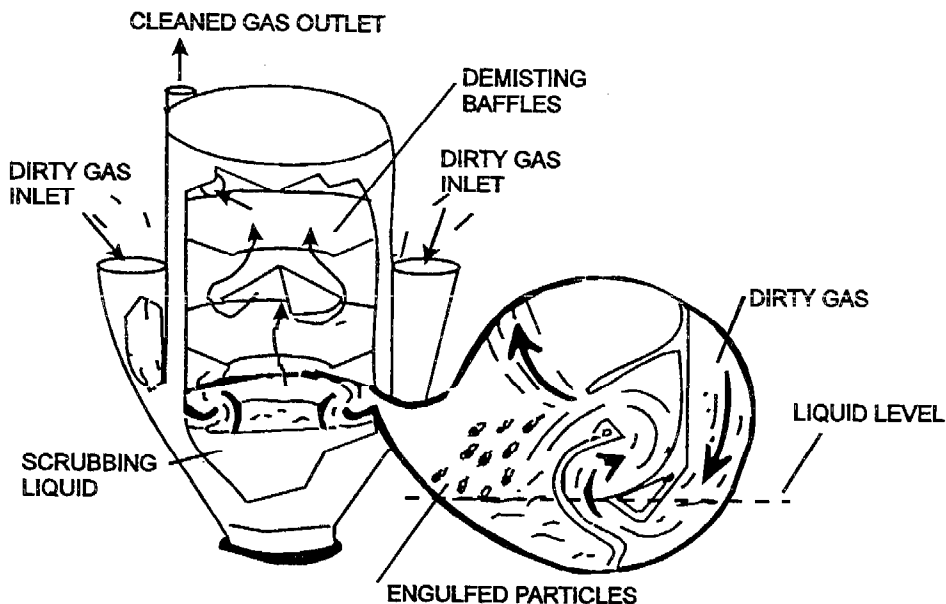


Figure 605.14 Orifice Scrubber

605.9 EJECTOR VENTURI SCRUBBERS

Ejector venturi scrubbers are somewhat unique scrubber designs in that they use a single high pressure spray nozzle which induces a flow of the dirty gas from the process being controlled. The injection of scrubbing liquid from the high pressure nozzle creates a lower relative pressure downstream of the nozzle, causing the gas stream to flow from the process to the control device. Furthermore, the large difference in velocity between the particles in the gas stream and the scrubbing liquid is created by the velocity of the liquid droplets. Unlike most other scrubber designs the majority of energy in this scrubbing system is supplied by the spray of a liquid instead of the use of centrifugal fans on the gas stream.

600 SCRUBBERS

Efficient particle collection is primarily through impaction of water droplets with particles from the large difference in velocity between the relatively slow moving gas stream and the fast moving droplets.

The Steam-Hydro® scrubber uses steam ejection and water sprays. In this scrubber the ejector is primarily made to atomize the scrubbing liquid. Steam-Hydro® scrubbers generally also use centrifugal fans to help move the gas stream. The steam, which is ejected at supersonic velocities, and the water droplets move at extremely high velocities and impact particles in the converging section of the device after the spray nozzles.

Gas ejector scrubbers can provide efficient gas absorption and can efficiently remove particles down to the submicron range. Several ejector scrubbers may be put in series to provide the necessary particle removal efficiency of very small particulates and to provide the necessary pressure drop.

605.10 GAS EJECTOR SCRUBBERS

These types of scrubbers have gas ejectors that accelerate the pollutant gas stream to a high velocity. A ring of spray nozzles around the end of the ejector inject scrubbing liquid into the gas stream.

The spray nozzles help promote droplet atomization and the shearing forces on the droplets from the expanding gas stream help atomize the liquid. The gas and liquid droplets flow through a converging duct section where turbulent mixing occurs.

These scrubbers can also remove particles in the submicron range and can be used in series to increase efficiency.

605.11 CONDENSATION GROWTH SCRUBBING SYSTEMS

Condensation growth scrubbers are complicated systems designed to remove particles in the submicron range from a gas stream. The primary method used to remove fine particulates is by conditioning of the gas stream. The gas stream is conditioned by the addition of large amounts of water vapor. Adding water vapor helps cool the gas stream and promotes the condensation of water vapor

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

on particles. Water vapor condensing on particles increases their mass and makes them easier to collect. Figure 605.15 illustrates a condensation growth system for an incinerator. Condensation growth systems work well for the control of particulates from combustion and other high temperature flue gas streams. Gas streams from these processes may be over 1800°F. For systems that have relatively cool gas streams, low pressure steam may be injected into the gas stream.

**Primarily for
Combustion
Processes**

After the gas stream passes through the initial control device (a venturi scrubber in this case) the gas stream contains a large amount of water vapor. The gas stream may be 40 to 60% by volume water vapor.¹ Water vapor is removed from the gas stream by condensation by a packed bed vessel, spray tower or similar device (Fig. 605.15).

The second control device, which is also a venturi scrubber in this case, removes a majority of the particles from the gas stream. The water spray for the second scrubber may come from a cooling tower. Scrubbing liquid in the condensation growth scrubbing system is kept as cold as possible. A cooling tower is used to cool recirculated scrubbing liquid by the removal of sensible heat.

Sensible heat is the energy that changes the temperature of the scrubbing liquid (usually mostly water). This is opposed to latent heat which is the energy that vaporizes a liquid or melts a solid. The temperature does not change when ice is melting or when water is being boiled into a vapor.

606 CYCLONE SYSTEMS AND DESIGNS

Cyclones, also called mechanical collectors, are widely used particle collection devices that are cylindrically shaped with a cone on the bottom (Fig. 606.1). Cyclones are low in cost and cheap to operate and maintain, but they have a relatively low collection efficiency for small sized particles. Most cyclones are suitable for medium sized particulates between 15.0 and 40.0 microns.

**Medium Sized
Particulate or
Larger**

In the last few years, new precisely designed, ultra high efficiency cyclones, that reach 99% collection efficiency with particles as small as 5.0 microns, have been developed. New ultra high efficiency cyclones are designed with the aid of computer modeling to accurately take into account the characteristics of

600 SCRUBBERS

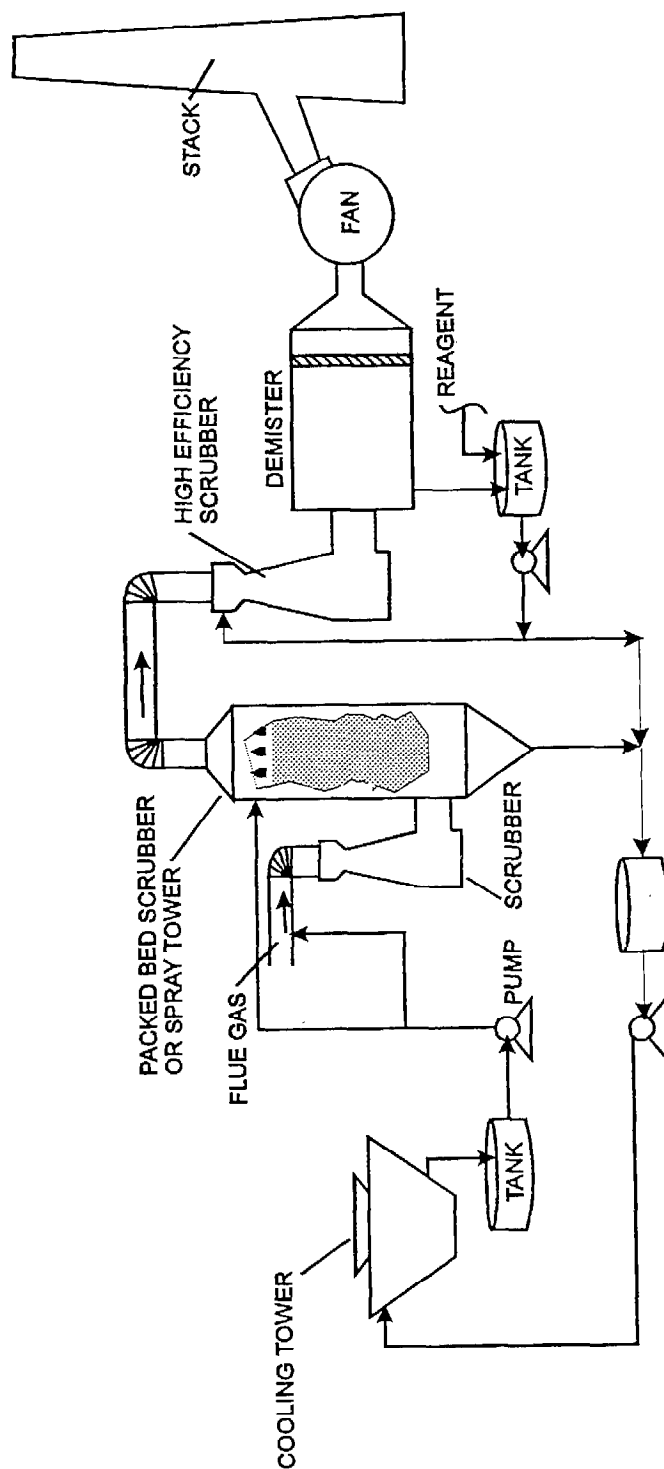


Figure 605.15 Condensation Growth Scrubber System

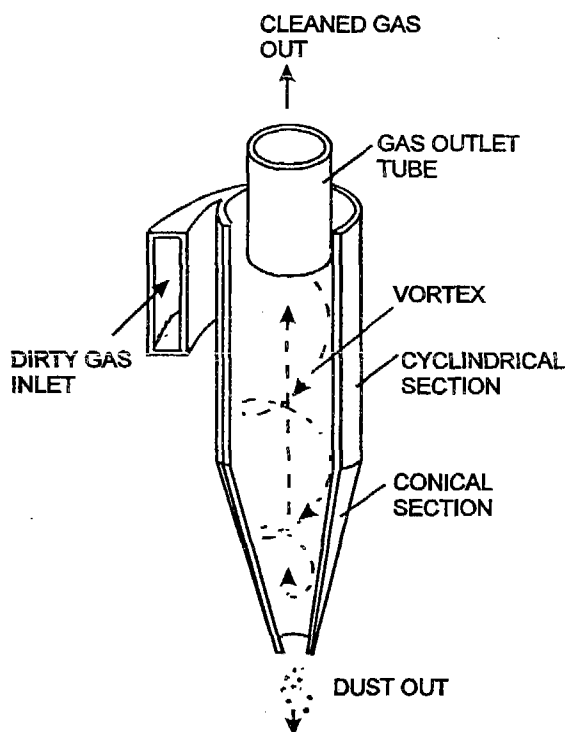


Figure 606.1 Large Diameter Cyclone

particulate matter and the gas flow. Particulate samples are taken to a laboratory and the aerodynamic size distribution of the particulates is developed to aid in the design.

Cyclones can be designed to handle a wide range of waste streams. The devices are used to remove large-sized abrasive particles for air pollution control and to recover product from a process. Cyclones help reduce the dust load and wear on control devices downstream of the cyclone. They can handle waste streams that are at high temperatures and with medium or coarse particulates. Some of the industrial processes cyclones are often used for include: feed mills, lumber mills, cement plants, and smelters.

606.1 CYCLONE COLLECTION MECHANISMS

A particle-laden gas stream enters a cyclone tangentially, forcing the gas to move in a vortex shape. This motion is called cyclonic motion, which is a spinning type of motion similar to the motion seen in the vortex of a whirlpool

Three Important Forces in Cyclone

or tornado. The gas stream normally has a velocity between 20 and 50 ft/sec as it enters the device. Particles are unable to make the sharp rotation of the gas stream because of their inertia and are forced outward toward the wall of the cyclone (Fig. 606.2). The particles strike the wall and fall down to the bottom of the cyclone. The gas makes a sharp, 180° change in direction at the bottom of the cyclone and the cleaned gas stream rises up the center of the cyclone, in an inner vortex, and exits through the top of the device (Fig. 606.1). At the bottom the gas stream breaks away from the particles. Usually only .5 to 3 revolutions are made within the cyclone by a gas stream.

The three important forces that act on the particles in the cyclone are centrifugal force, gravitational force, and drag force. Centrifugal force acts on the particles because of the rotation within the cyclone. The force is due to the acceleration that occurs from the rotational motion and it is the main force that causes particles to leave the gas stream.

$$a_c = v^2/r$$

where:

a_c = Centrifugal acceleration (ft/sec²)

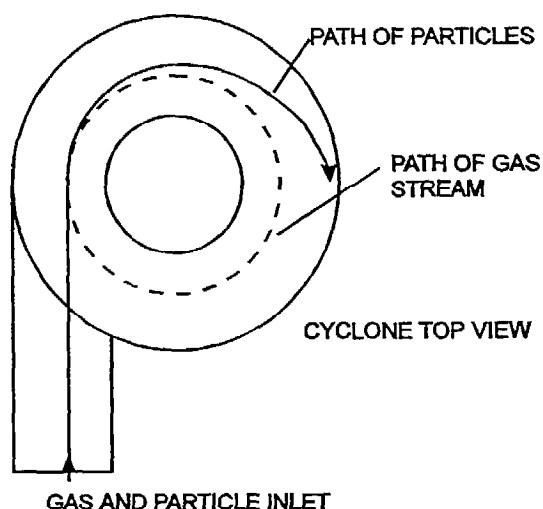


Figure 606.2 Movement of Particles Across Gas Stream Lines

600 SCRUBBERS

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v = particle velocity (ft/sec)

r = radius of motion (ft)

From Newton's law an accelerating mass will be acted on by a force ($F = ma/g_c$); therefore, the force on a particle is:

$$F = [m(v^2/r)]/g_c$$

where:

m = particle mass (lbm)

F = force (lbf)

g_c = lbm-ft/lbf-sec²

Once particles move to the outer part of the cyclone, they are caught in a thin layer of laminar air and their rotating motion is opposed by drag forces. Gravity can then pull the particles down into the hopper. At the outer boundary of the cyclone the velocity is theoretically zero and increases constantly up to the velocity of the gas stream. The force due to gravity is:

$$F = ma/g_c$$

where:

a = acceleration due to gravity (32.2 ft/sec²)

The higher the velocity of the gas stream through a cyclone the higher the collection efficiency. Once the velocity of the gas stream gets over 80 ft/sec the efficiency starts to slightly decline because of increased turbulence. At higher velocities and dust loads, the cyclone will wear more rapidly from scouring.

606.2 LARGE DIAMETER CYCLONES

Large diameter cyclones are generally ones with a diameter over 1.0 feet. The main parts of the cyclone include: the inlet, the cylindrical section, the conical section and the gas outlet tube (Fig. 606.1). The inlet is an important part of the cyclone design because turbulence in the inlet can interfere with the cyclonic motion.

600 SCRUBBERS

Series and Parallel

The narrowing conical portion of the cyclone has a continually smaller area for the gas, forcing the gas stream to move faster, keeping the particles on the outside wall and preventing them from reentering the gas stream. The gas outlet tube helps create the formation of the vortex and prevent the gas stream from short circuiting out the exit.

Most large diameter cyclones have a top, tangential inlet. The most common types of cyclone inlets are illustrated in Figure 606.3. The addition of deflector vanes can reduce the turbulence in the inlet and lower the pressure drop, but the vanes can also impair vortex formation and lower collection efficiency. The involute entry design usually improves efficiency due to improved vortex formation. It can also reduce the pressure drop from turbulence. Helical designs are also made to reduce the cyclone pressure drop and improve collection efficiency.

Another large diameter cyclone design, known as the bottom inlet cyclone, is illustrated in Figure 606.4. The bottom inlet configuration is not as common. This configuration does not have an outlet gas tube.

Cyclones can be arranged in series or parallel arrangements to increase particle removal efficiency or increase gas flow capacity (Fig. 606.5). In the series arrangement, the gas exiting the first cyclone is passed through a second to remove remaining larger-sized particles. In the four-cyclone parallel arrangement, higher velocities can be applied and higher collection efficiencies can be attained. Furthermore, only a single discharge is required. This type of cyclone design is good for large abrasive particles and is used in the cement industry.

606.2.1 Solids Discharge Valves

The main types of discharge valve systems for large diameter cyclones are shown in Figure 606.6. A solids discharge valve is a necessary part of a cyclone when it operates under negative pressure. A positive pressure system does not need a discharge valve as long as there is a system to contain gathered particulate matter. The simplest design is the simple manual slide gate. It may be used in a batch process. An operator would have to remember to open the gate after a process had concluded. If excessive amounts of particles gather at the valve they may start to reentrain into the gas stream.

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VOC CONTROL
DEVICES/
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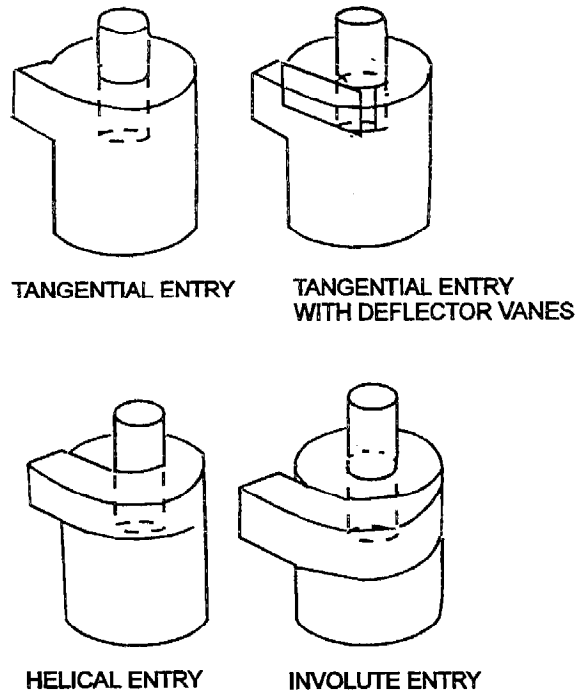


Figure 606.3 Cyclone Inlets

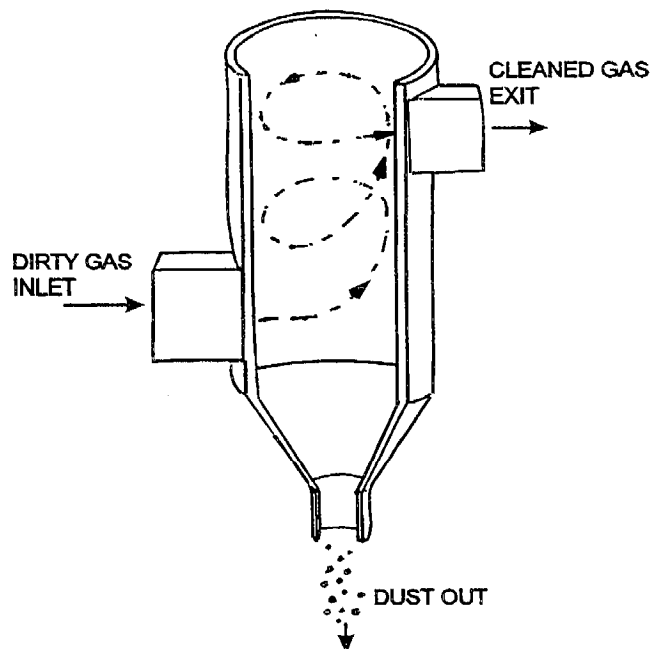


Figure 606.4 Bottom Inlet Cyclone

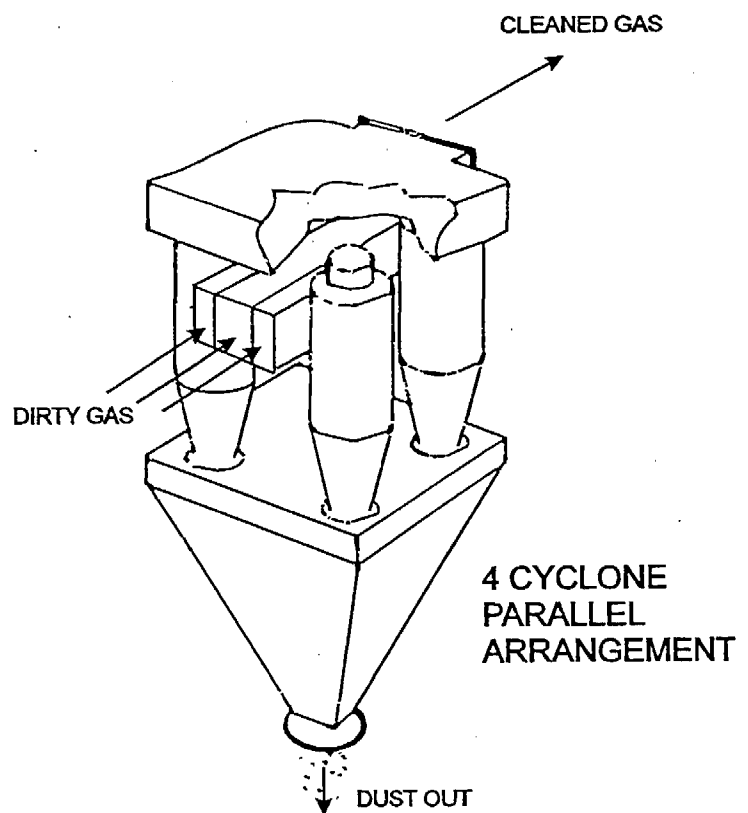
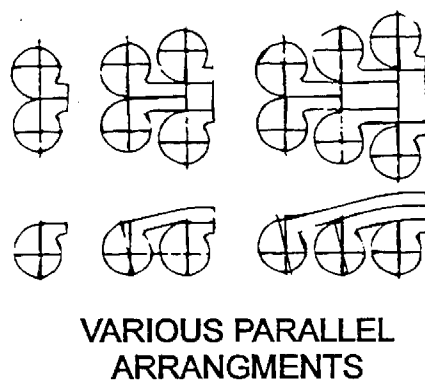
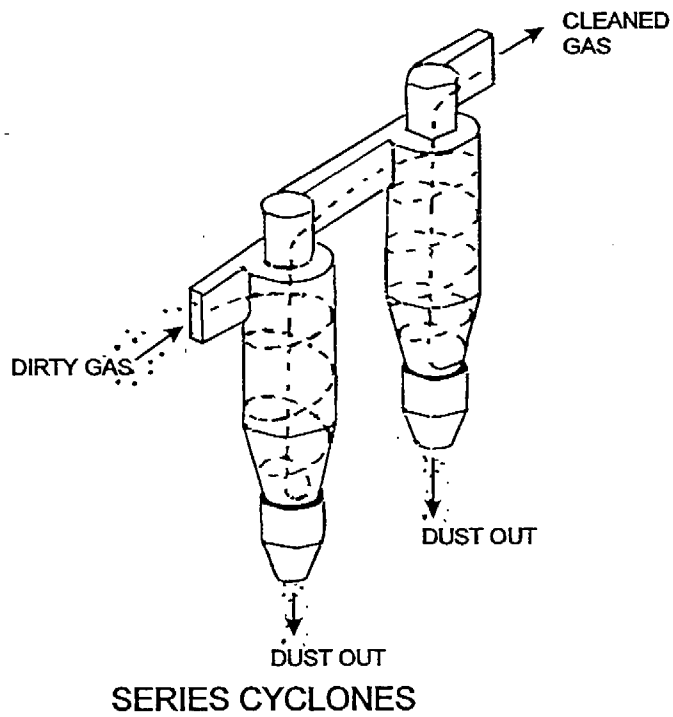
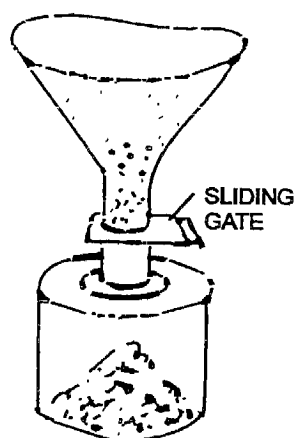


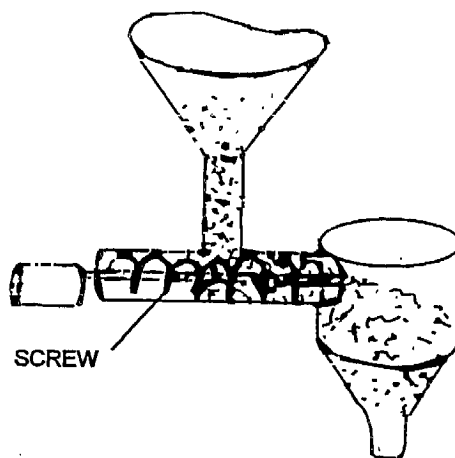
Figure 606.5 Series and Parallel Cyclone Arrangements

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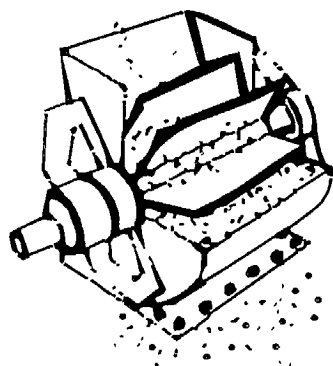
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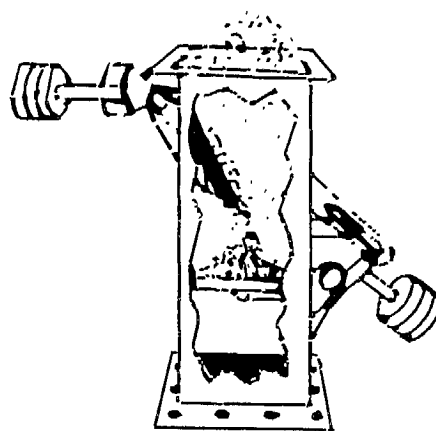
MANUAL SLIDE GATE



DISCHARGE SCREW FEEDER



ROTARY VALVE



AUTOMATIC FLAP
VALVE

Figure 606.6 Solids
Discharge Valves

The discharge screw feeder can be used for an intermittent or continuous process. As the screw turns it pushes collected particles to a disposal area. The rotary valve has a series of paddles on an axle. As it turns, a load of particles is gathered between each pair of paddles and discharged from the bottom. In the automatic flap valve, a flap opens and closes after regulated increments of time, dropping collected particles into the disposal area.

It is important that the solids discharge valve have a good seal, especially if the cyclone is operating under negative pressure. The discharge screw feeder does not have gas-tight sealing; it can only operate under negative pressure if an additional airtight discharge valve is put between the cyclone and the discharge screw.

606.3 MULTI-CYCLONES

The efficiency of cyclones can be increased by using a multi-cyclone collector (Fig. 606.7). A multi-cyclone is made of a number of small diameter cyclones inside of a single vessel operating in parallel. A small cyclone is one less than 12 inches in diameter and they are usually at least 6 inches in diameter. A large number of small cyclones is required because large flows must be handled and a small diameter cyclone by itself is not big enough. The number of tubes may range from 9 to over 200. These cyclones also differ somewhat from the large diameter cyclone (Fig. 606.8). Small diameter cyclones for a multi-cyclone have spinner vanes inside at the top to initiate the cyclonic motion on the gas stream.

Spinner Vanes

At the inlet side of the multi-cyclone, the tubes are the longest and the length decreases toward the outlet side of the device. This is done because there is a pressure drop for each succeeding row of cyclones and the longer cyclones at the inlet have a larger pressure drop than the cyclones toward the exit. This prevents the gas stream from trying to go through one row of cyclones. The air takes the path of least resistance, but with the different cyclone lengths, the air is distributed between them evenly.

Two Tube
Sheets

There are two tube sheets on the upper part of the multi-cyclone and the dirty gas enters the cyclone between the two tube sheets. The upper tube sheet (clean gas tube sheet) separates the dirty gas from the atmosphere and it separates the clean gas from the dirty gas. It is made in a step-like fashion or a steep slope because of the different lengths of tubes. The dirty gas tube sheet is

600 SCRUBBERS

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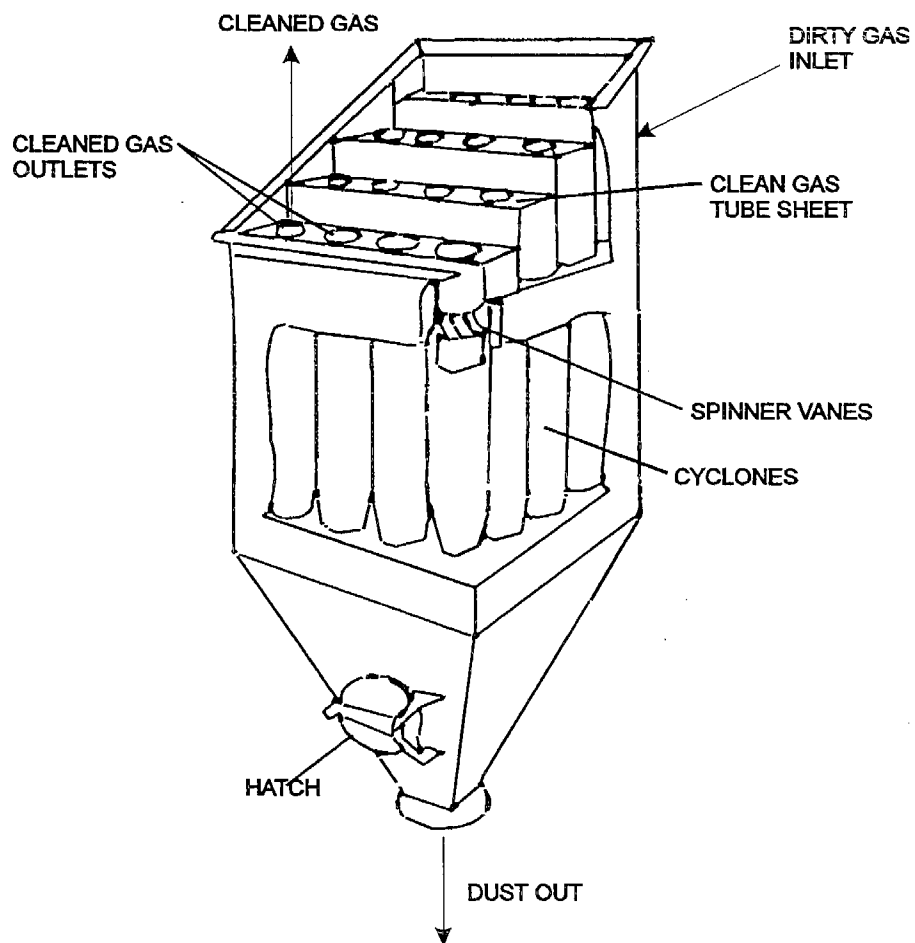


Figure 606.7 Multi-Cyclone

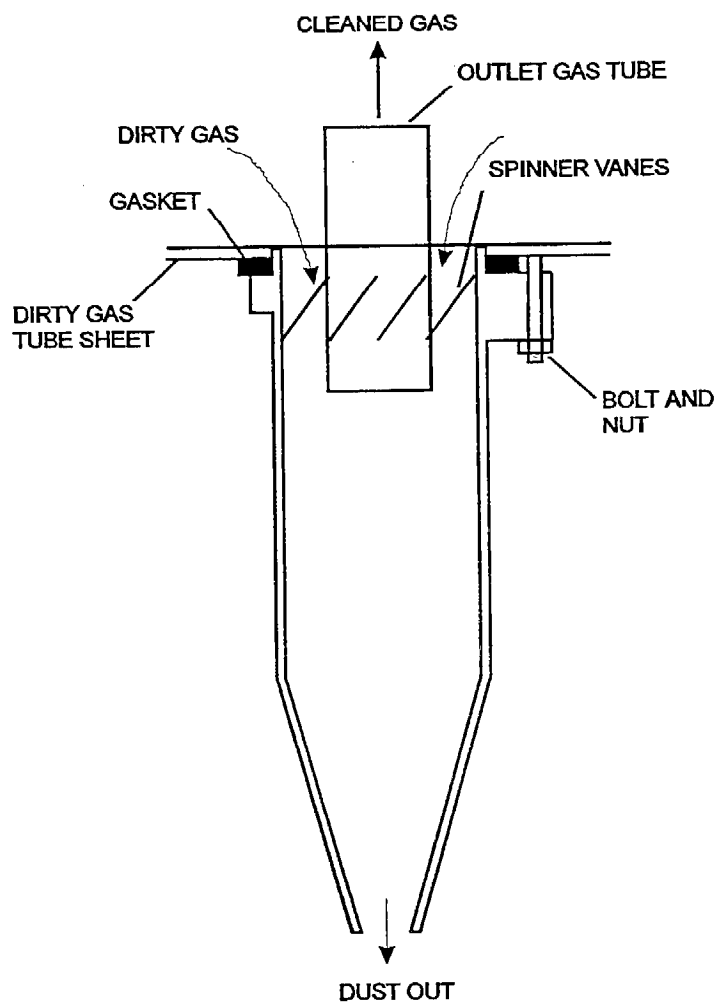


Figure 606.8 Small Diameter Cyclone
from Multi-Cyclone

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

flat and is usually the main support for the cyclones (Fig. 606.8). A good seal between the cyclones and the tube sheets is required. If there is a leak in the clean gas tube sheet, excessive dust emissions may result. If gas leaks through the lower tube sheet, dirty gas will bypass the cyclone and enter the hopper area. Gaskets may be used to provide sealing between the tube sheets and cyclones. In some designs the clean side tube sheet may be welded to the cyclone to provide sealing.

Particles are removed from the gas stream in the same manner that they are removed in a large diameter cyclone. An outer vortex is formed by the spinner vanes, forcing particles to hit the wall of the cyclone and fall to the bottom. The gas stream makes a 180° turn at the bottom of the cyclone, leaving particles behind, and ascends the cyclone in an inner vortex out the top of the cyclone. In the small diameter cyclone the gas stream spins faster and more centrifugal force is applied to the particles, increasing the collection efficiency. The gas stream will make 1.5 to 3 revolutions within the cyclone.

The pressure drop across a cyclone is between 1 and 5 inches of water. 90% of the pressure drop in a multi-cyclone occurs across the spinning vanes. The efficiency of a multiple cyclone can be as high as 90% for particulates in the 5.0 to 10.0 micron range.¹⁰

A cyclone's efficiency can be increased by increasing the particulate density, the cyclone length, the number of gas revolutions, the ratio of the cyclone body diameter to the outlet diameter, particulate diameter, and the smoothness of the inside of the cyclone. With more particles in a cyclone, agglomeration is more effective since there are more particles to collide with each other. Larger numbers of revolutions of the gas stream within the cyclone increase the chances of particulates of being pushed out to the sides of the device and being collected. Taller thinner cyclones are more efficient. Increasing the inlet area, gas outlet diameter, and gas density decreases the efficiency of a cyclone.

606.4 CYCLONIC SCRUBBERS

Cyclonic scrubbers, which are also known as centrifugal spray scrubbers, use a cyclonic motion on the gas stream. The motion of the gas stream has a higher velocity and therefore increases the collection over that of spray scrubbers. Impaction and interception are the major collection mechanisms employed in cyclonic scrubbers.

The Pease Anthony Cyclonic Scrubber is one of the most common cyclonic designs that have been used. The central liquid spray in a Pease Anthony Cyclonic Scrubber gets caught in the upward swirling motion of the gas stream. As liquid droplets wet particles in the air stream, centrifugal force pushes liquid droplets out to the sides of the scrubber. The wetted particles are then washed by the continual spray of liquid to the bottom of the scrubber and out the exit. The liquid spray in a cyclonic scrubber prevents the reentrainment of particulates into the exiting gas stream. The upper portion of the Pease Anthony Cyclonic Scrubber is not wetted by the spray, in order to allow time for wetted particles to reach the walls of the scrubber.

Most Pease Anthony Cyclonic Scrubbers use 4.0 to 10.0 gallons of water for every 1,000 cfm of gas. The range of pressure drop is usually between 2.0 and 8.0 in. of water.¹⁰ The higher the velocity of the gas stream in the scrubber, the higher the collection efficiency tends to be.

606.5 CYCLONE THEORY

As with scrubbers, cyclone efficiency is highly dependent on particle size. A number of formulations have been developed for determining cyclone efficiency for different particle sizes. These formulations are applicable to large diameter cyclones and multi-cyclones. The main theories developed for calculating efficiency of a cyclone include the Lapple Theory (1951), Barth Theory (1956), Peterson and Whitby Experimental data (1965), Sproull Theory (1970), and the Leith and Licht Theory (1972).

The following is the Leith and Licht equation¹:

$$\eta_i = 1 - \exp(-2[c\psi]^{1/(2n+2)})$$

where:

η_i = Collection efficiency for particle of diameter i

c = Cyclone dimension factor; c is a function of the cyclone shape

ψ = Impaction parameter; ψ is a function of particle size and particle density

n = Vortex exponent; n is a function of temperature and gas velocity

furthermore:

$$\psi = [\rho_p d_p^2 v / (18 \mu D_c)] (n+1)$$

where:

d_p = Particle diameter, cm

ρ = Particle density, gm/cm

v = Inlet gas velocity, cm/sec

μ = Gas viscosity, gm/cm-sec

D_c = Cyclone diameter, cm

Large impaction parameters are associated with high particle collection efficiencies. It can be seen from the above equation that collection efficiency is related to the square of the particle diameter and is proportional to the inlet gas velocity. Furthermore, the collection efficiency is inversely proportional to the diameter of the cyclone. In order to apply these equations, Leith, reference thirteen, should be consulted.

606.5.1 Predicting Pressure Drop

The pressure drop is an important parameter for the design of a cyclone. The pressure drop is related to the cost of operating a cyclone. Higher pressure drops will mean higher operating costs but increased collection efficiencies.

The following equation developed by Shepard and Lapple can be used to predict pressure drop¹:

$$\Delta p = [v^2 \rho_g / 2 g \rho_m] K_c [H_c B_c / D_c^2]$$

where:

ρ_g = Gas density

ρ_m = Density of manometer fluid used to measure v (inlet gas velocity)

g = Acceleration due to gravity

K_c = Empirical constant (16 for cyclone with tangential inlet, 7.5 for one with an inlet vane)

$H_c B_c$ = Inlet height and inlet width respectively

D_c = Cyclone body diameter

**Cyclone
Pressure Drop
Equation**

600 SCRUBBERS

The correlation coefficient between calculations with the above equation and experimental data is 0.77.¹³ It can be seen from the above equation that pressure drop is a function of the velocity squared.

607 MIST ELIMINATION

Mist elimination is the removal of entrained water droplets from the treated gas stream and is a very important part of scrubbing. This process may also be called demisting or entrainment separation. If entrained water droplets, which also contain captured particles, are not removed from the gas stream before it leaves the stack, emissions of dissolved and suspended particulates may result. This could lead to violations of air pollution regulations and public nuisances or damage to fans. Problems with mist elimination can negate all the previous work done on a gas stream for the removal of particulates.

Some larger sized droplets may drop out of a gas stream by gravity, but many droplets are extremely small and are not affected a great deal by gravity. Most droplets from scrubbers may range between 50 and 1000 microns in diameter. Effective mist eliminators can remove 99 to 99.9% of entrained water droplets.

607.1 TYPES OF MIST ELIMINATORS

Many types of mist eliminating devices have been developed, but most of them are categorized within the following types: cyclonic vessels, chevrons, mesh pads, and woven pads. Mist eliminators generally remove droplets from gas streams by inertial impaction of droplets on these devices and centrifugal force applied to the gas stream.

Mist eliminators may be used in a horizontal or vertical gas flow configuration. When mist eliminators are used on a vertical gas stream, liquids removed from the gas will drip from the eliminator from the force of gravity on the liquid against the flow of the gas stream. Liquids collected by mist eliminators used on horizontal gas flows will not drip against the flow of the gas, so horizontal mist eliminators can handle higher gas velocities and liquid loadings.

607.1.1 Cyclonic Vessels

Cyclonic mist eliminators operate similarly to large diameter cyclones. They usually have a tangential gas entry and vanes inside to help guide the gas flow in a cyclonic motion. The gas stream rotates around the inside of the vessel as it rises. The gas stream will usually make 0.5 to over 2.0 revolutions in the vessel. The rotation of the gas stream produces centrifugal force on the droplets, causing them to impact the side of the demister vessel. Figure 607.1 shows a cyclonic demister on a venturi scrubber.

Cyclonic vessels have reasonable removal efficiencies for velocities close to design velocities. As velocities in a cyclonic demister get very high or low, droplet removal efficiency rapidly decreases.¹ Table 607.1 shows the gas flow ranges applicable for most popular eliminator designs.¹²

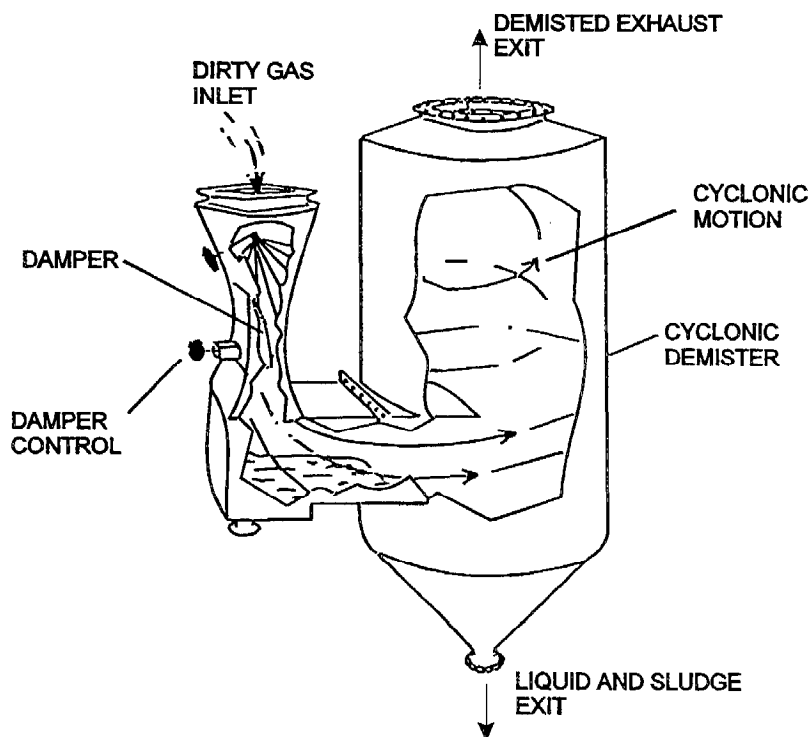


Figure 607.1 Cyclonic Demister with
Venturi Scrubber

600 SCRUBBERS

Table 607.1
Velocities for Common Mist Eliminator Designs 12

| Eliminator Design | Orientation | Gas Velocity (ft/sec) |
|-------------------|-------------------------|-----------------------|
| Zigzag | Horizontal | 15-20 |
| Zigzag | Vertical | 12-15 |
| Zigzag | 30 deg. from horizontal | 16-22 |
| Cyclonic | All | 100-130 |
| Mesh | Horizontal | 15-23 |
| Mesh | Vertical | 10-15 |
| Tube Bank | Horizontal | 18-23 |
| Tube Bank | Vertical | 12-16 |
| Euroform T271 | Vertical | 10-20 |

Cyclonic demisters are especially good for the removal of large droplets or as an initial demister. They are also much less prone to plugging than other demisters.

607.1.2 Chevrons

Chevrons are basically devices composed of zigzag baffles which force a gas stream to turn sharply (Fig. 607.2). Liquids collect on the blades of the chevron and drain downward by gravity.

The number of passes in a chevron is counted by the number of baffles in the device or by the actual number of air passages, which is equal to the number of baffles minus one. Chevrons with two to six passes are common and three are usually sufficient.¹² Another way which chevrons are identified is by the number of turns made by a gas stream going through the chevron.

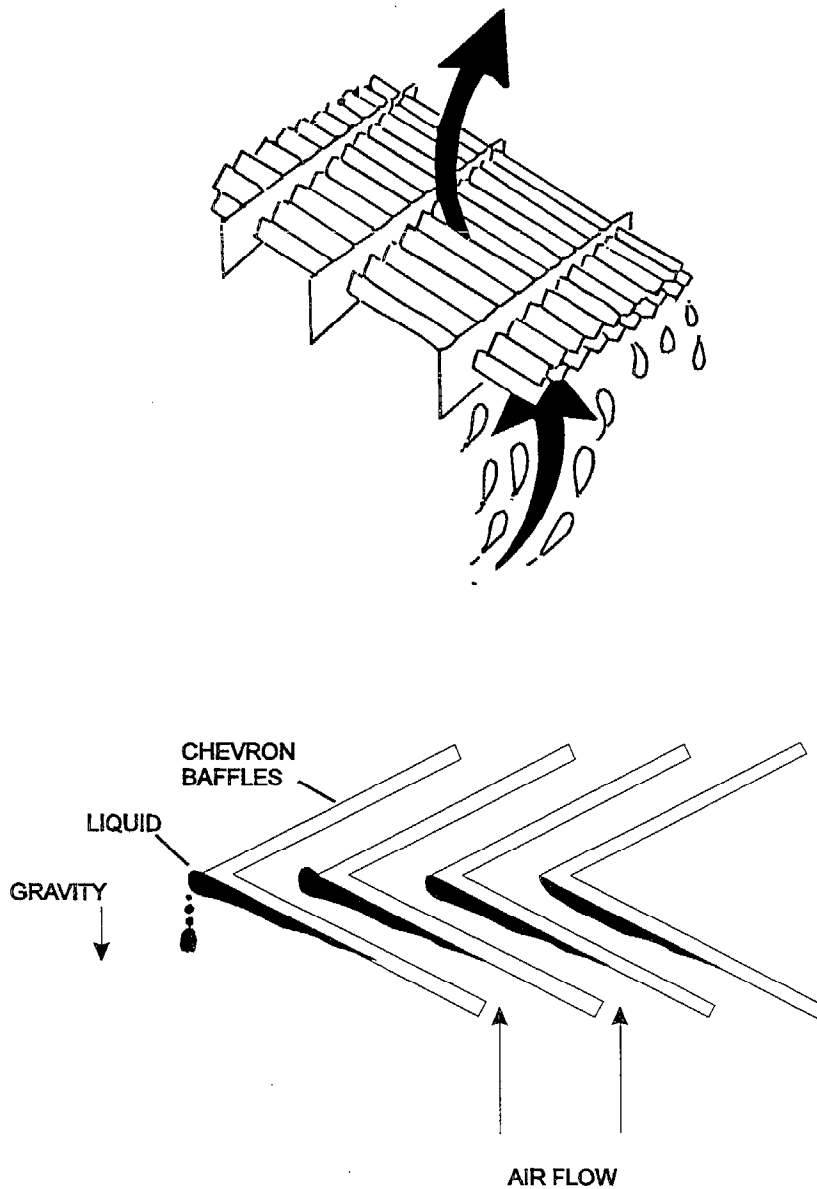


Figure 607.2 Chevron Mist Eliminator

600 SCRUBBERS

If the gas velocity through a chevron gets too high, liquids can be reentrained in the gas streams. High gas velocities push liquids on the blades toward the outlet of a chevron. Most chevrons can handle mist elimination for a gas stream up to approximately 20 ft/sec.¹¹ Excessive gas velocities are often caused by the buildup of solids or plugging of part of the chevron. In order to help prevent solid accumulation, chevrons are equipped with clean liquid sprays. The sprays can be designed to operate intermittently, spraying the chevron once a day or more, depending on the solids load. The sprays can be put at the inlet or the outlet of the chevron.

Some chevrons are equipped with liquid phase separation chambers to prevent liquids from being pushed to the outlet and being reentrained (Fig. 607.3). These types of devices are often included on horizontal eliminators.

607.1.3 Mesh Pad Mist Eliminators

Mesh pads are generally made of randomly interlaced fibers (Fig. 607.4). They are made of metallic or nonmetallic materials such as stainless steel or plastic. The pads are usually between 4 and 12 inches thick and they average about 6 inches in thickness. They are usually oriented horizontally, but they may be placed 0 to 45° from the horizontal in a scrubber. Different mesh types can be

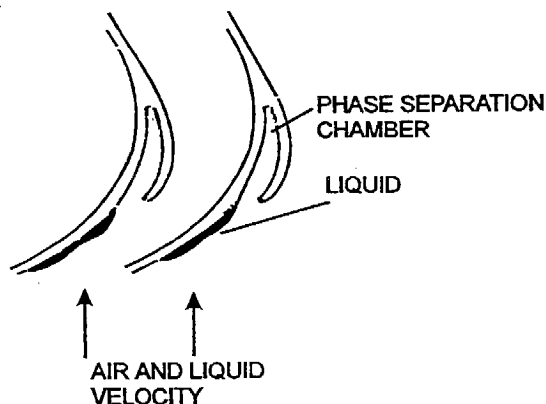


Figure 607.3 Mist Eliminator with
Phase Separation Chambers

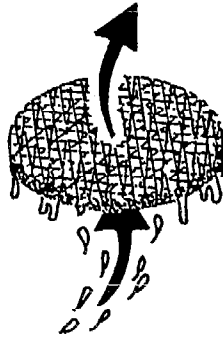


Figure 607.4 Mesh Pad Mist Eliminator

identified by their densities. Most mesh pads are between 5 and 10 lbs./ft³ in density. The maximum velocity that a mesh pad can handle depends on the density of the mesh pad and the density of the gas.

Droplets are removed by mesh pads by impaction on the wire mesh. Droplets coalesce on the wire and fall by gravity.

607.1.4 Woven Pad Mist Eliminators

Woven pad eliminators are made of interlaced synthetic fibers in a layer structure. Woven pad mist eliminators are often called mesh pads in industry since the two mist eliminators are similar.

The inlet side of the woven pad has an open weave while the outlet side and the middle has a tighter weave. This allows larger droplets to be removed first at the inlet and smaller droplets to be removed toward the middle and exit. This helps prevent the mist eliminator from getting overloaded by an excess of liquid. The approximate range for gas flows for these eliminators is between 10 to 15 ft/sec.

600 SCRUBBERS

As with chevrons, mesh pads and woven pads are usually equipped with liquid sprays to prevent the accumulation of solids. An accumulation of solids can plug part of the eliminator, reduce the area of flow, create excessive pressure drops and increase liquid entrainment. Properly operating mist eliminators usually have a pressure drop between 0.5 and 4.0 inches of water.

608 SCRUBBER PLUMES

Unlike most other control devices, wet scrubbers produce plumes containing large amounts of water vapor. The water vapor in the plume usually condenses when it exits the stack of the scrubber, forming white puffs of steam. This can complicate visible emissions evaluations, since water vapor can mask illegal emissions.

The gas stream coming out of the stack may be hot, especially when the scrubber is controlling the flue gas from a combustion process. Warm air holds a lot more water vapor than cool air, so when the flue gas comes in contact with cooler atmospheric air, the flue gas cools and the water in the gas stream condenses, forming a plume.

The water vapor in the plume condenses when the gas stream is cooled to its dew point. Therefore, if the dew point of the flue gas exiting a stack is not reached until a distance above the stack exit, a "detached plume" will be created.

Weather Conditions

Weather conditions can have a large effect on the plume formed. When the weather is warmer, water vapor plumes will tend to be smaller and will dissipate more rapidly. When the weather is colder, plumes will tend to be larger and will take longer to dissipate. The amount of atmospheric air required to dilute a plume and condensation of the mists increases with increasing ambient relative humidity, decreasing ambient temperature and increasing moisture content in the effluent gas stream.

The two main characteristics of a water vapor plume are its whiteness in bright sunlight and wispieness.

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

The psychrometric chart is a graphical representation of air and water vapor mixtures (Fig. 608.1). The horizontal scale is the dry bulb temperature. The dry bulb temperature is the temperature of dry air. The diagonal lines are for the wet bulb temperature (also called saturation temperature). The curving lines are the relative humidity, which varies from 0 to 100%. Relative humidity is defined as the partial water vapor pressure divided by the saturation pressure. On the right side of the chart is the humidity ratio. It is the mass of water vapor per unit mass of dry air and is expressed as grains of moisture or pounds of moisture per pound of dry air.

Psychrometric Chart

Only two properties are required to be known to determine all the rest of the properties on the chart. In the field the two properties that are usually measured are dry bulb and wet bulb temperatures. The dry bulb and wet bulb temperatures are measured with a psychrometer. A psychrometer consists of two thermometers: one for the dry bulb temperature measurement and another one with a wick for the wet bulb temperature measurement. The dry bulb temperature is simply read off the dry bulb temperature scale. In order to get the wet bulb temperature, the wick is wetted and the psychrometer is swung around through the air. The psychrometer will then indicate the wet bulb temperature of the air. A point can then be put on the psychrometric chart indicating the properties of atmospheric air. The conditions of the flue gas at the stack can be measured or they are known, so a point indicating the flue gas conditions can be established on the chart. A straight line can then be drawn between the two points and if any part of the line crosses the 100% relative humidity line, a visible vapor plume will be formed.

Psychrometer

609 COMPONENTS OF THE OVERALL SCRUBBING SYSTEM

Figure 609.1 illustrates a simplified drawing of a scrubber system. Scrubbing system designs can vary widely and some components in the figure may not be in all systems. Furthermore, scrubbing systems have additional equipment that may not be shown here.

After an industrial process, such as combustion, the dirty gas from the exhaust of the process must be captured and sent to the scrubbing system. This may be done by hoods which draw in the particle or odor-laden gas. The gas may then

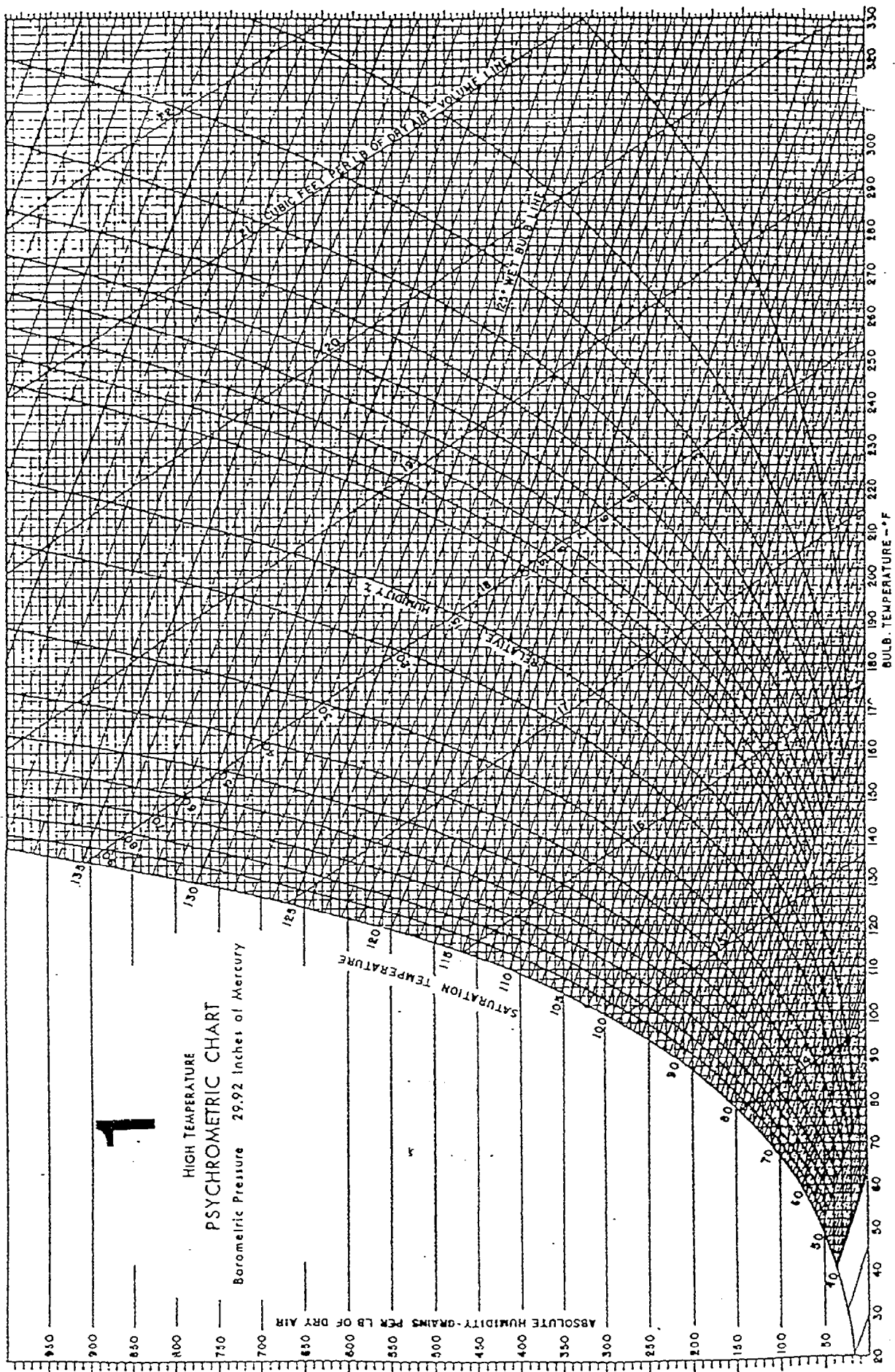


Figure 608.1 Psychrometric Chart

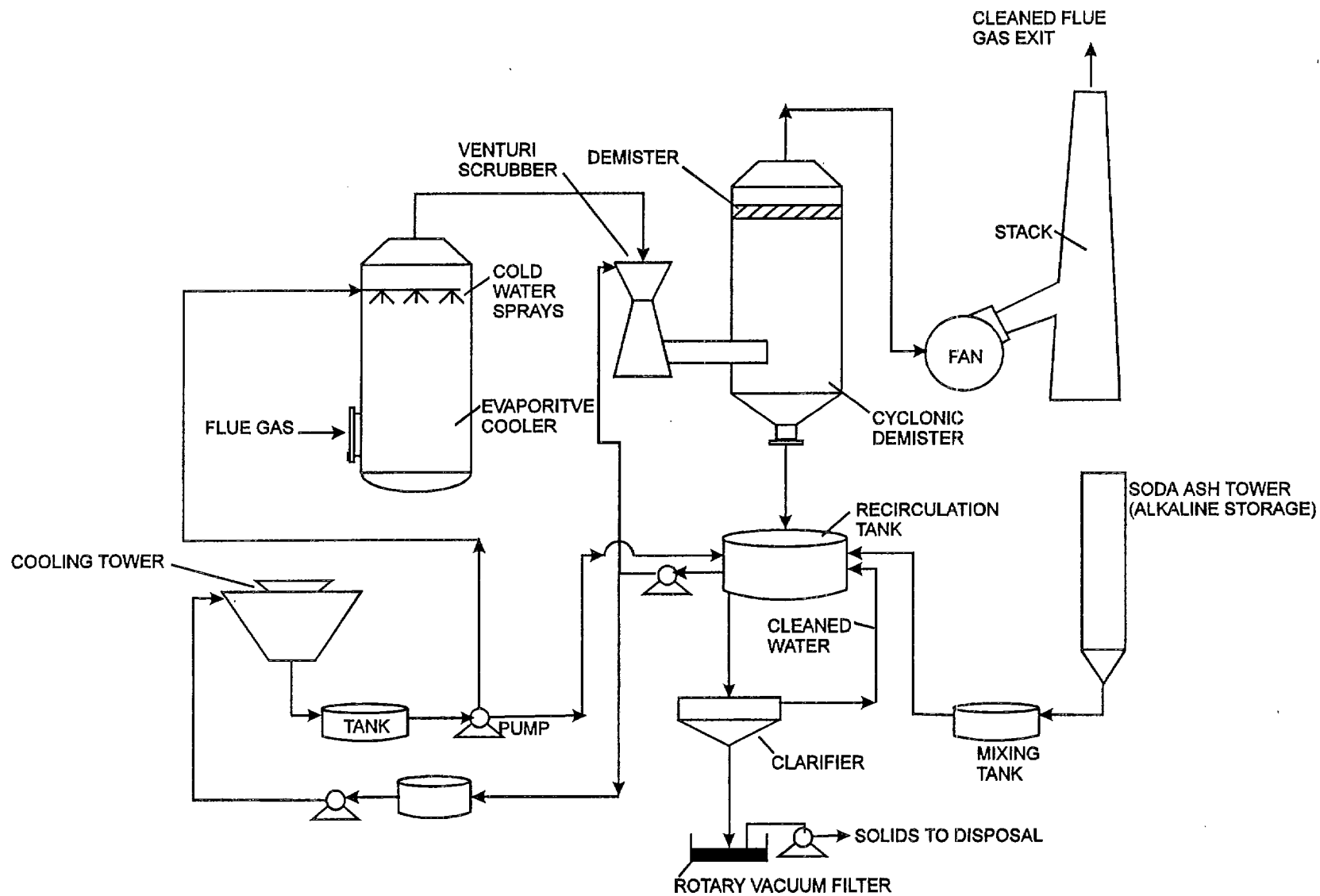


Figure 609.1 Simplified Scrubber System

600 SCRUBBERS

Recirculation Tank

enter a spray tower for gas conditioning. In the tower the gas is cooled, humidified and larger sized particles may be removed. It may be important to cool a gas stream, especially when the gas stream is very hot, to prevent damage to the scrubber and droplet evaporation.¹ Then the gas stream goes through the main scrubbing device where particles are captured by liquid droplets. The gas stream, containing entrained liquid droplets laden with particles, then goes through a demister and the droplets are removed. The clean gas stream then flows out the stack and into the environment.

Scrubbing liquid is recirculated through a scrubbing system to minimize the amount of water that must be treated and discharged. Scrubbing liquid that does not get entrained in the air stream when it is sprayed in a scrubber flows to the bottom of the unit and out to a sump or recirculation tank. Other liquid streams from mist eliminators and gas conditioners may flow to the recirculation tank.

Alkaline substances are added to the recirculation tank to maintain the proper pH. If the scrubbing liquid gets too acidic, damage to spray nozzles, scrubbing vessels and other equipment in contact with the liquid could occur. The water must also not become too alkaline. Precipitates of calcium and magnesium could occur in the scrubbing liquid system and eventually plug the equipment. Lime, soda ash, limestone, and sodium hydroxide are common alkali materials added to the scrubbing liquid.¹

Clarifier

In order to control the amount of solids in the scrubbing liquid, a small amount of the liquid is sent from the recirculation tank to a clarifier. The clarifier is a tank where solids are made to separate from the liquid by gravity. Solids may be removed by allowing liquid from the bottom of the clarifier with a high solids content to flow out and be pumped through a rotary vacuum filter. The rotary vacuum filter pumps the liquid through a filter, removing solids which are then disposed of. Clean liquid from the upper portion of the clarifier and the filtered liquid are pumped back to the recirculation tank. Liquid for the scrubbers is continually pumped from the recirculation tank.

Some water is continually lost in the scrubbing system from the removal of solids and from the stack. Additional water is usually added to the scrubbing system in the recirculation tank. Clean water may also be continually used for demisters and gas conditioning or humidification.

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

609.1 HOODS AND FANS

As discussed in the Introduction, pollutant laden air from a process must be captured and sent to a control device. This is usually done with hoods. Fans are an important part of a scrubbing; they provide the energy to draw the particulates from the source to the scrubber. They often provide the energy to create the large difference in velocity between droplets and particles necessary for efficient scrubbing. A discussion concerning hoods and fans is in the Introduction.

609.2 PUMPS

Pumps are mechanical devices that impart energy to a fluid, and are used to transport the scrubbing liquid throughout the scrubbing system. Pumps mainly are in two categories: Positive displacement and kinetic. The most common positive displacement pumps include reciprocating action pumps (which use pistons, plungers, diaphragms or bellows) and rotary action pumps (using vanes, screws, lobes or progressing cavities).² The primary kinetic pumps are centrifugal pumps, which have rotating impellers, transforming kinetic energy into static pressure. The impeller is usually driven by an electric motor, steam turbine, or engine. The machine delivering the power is often called the "driver." Centrifugal pumps are usually used to circulate liquor streams and liquid from the top of the clarifier (clarifier overflow streams). Positive displacement pumps tend to be good for handling scrubbing liquid containing a high solids content. Diaphragm pumps, for example, may often be used to handle the liquids from the bottom of the clarifier (clarifier underflow), which contains a lot of solids. Most positive displacement pumps are less prone to plugging from solids.

Some pumps are equipped with strainers to remove pieces of metal and debris from scrubbing liquid. Strainers are not used on pumps where the solids content of the scrubbing liquid is high and tends to clog the strainers.

**Positive
Displacement
and Kinetic**

600 SCRUBBERS

Pumps may be equipped with suction check valves and discharge valves. Suction check valves allow flow in only one direction and prevent air from getting into the pump during a power outage or shutdown. The discharge valve can be used to adjust the flow from a pump.

609.3 CLARIFIER SYSTEM

Scrubbing liquid enters the clarifier through a purge line from the recirculation tank. The solids in the water separate by gravity. The cleaner liquid tends to stay near the top of the clarifier and the solids tend to sink to the bottom. The liquid with a high solids content at the bottom of the clarifier is removed and run through a filter to remove solids.

609.4 COOLING TOWERS

In some large scrubbing systems, especially those handling gas streams from incinerators and other high temperature combustion processes, a cooling tower may be used to cool and condense the liquid and vapor from the conditioning of a gas stream. In most gas conditioners and condensation growth scrubber systems, it is best if the liquid is as cold as possible.

Cooling towers are generally rectangular structures that may be divided into a few independent cells. Within the stack or body of a cooling tower is a large fan which draws air up through the cooling tower from the sides of the device. As the air is being pulled up, hot or warm water is sprayed down from the top of the tower. Water trickles down through the tower by gravity over baffles or packing, which help maximize the surface area of the water and the contact between the air and water. The air and water also move in a counter-flow arrangement which helps improve contact between the two flows. Heat is primarily removed from the water through evaporation of water in the cooling tower. This process is also called evaporative cooling. Cooled water falls to the bottom of the cooling tower in a basin, where it can then be pumped to condition the gas stream or provide scrubbing. Depending on atmospheric conditions, a plume may often be seen from the stack of a cooling tower. For more information on cooling towers, see the Petroleum Refining Technical Manual.

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

609.5 INSTRUMENTATION

Instrumentation is required for a scrubbing system in order to protect the components of the system and monitor scrubber performance. The following is a list of the major parameters that are monitored and the part of the scrubbing system they are monitoring:

Gas temperature:

- Scrubber inlet and outlet

Static pressure drop:

- Wet scrubbing vessel
- Demister

Liquid pressure:

- Recirculation pump discharge
- Scrubber liquid distribution headers

Liquid pH:

- Recirculation tank or recirculation liquid stream

Liquid flow rate:

- Recirculation liquid stream
- Purge liquid stream

Temperature

Temperature gauges on the gas inlet side of a scrubbing vessel monitor the temperature of the dirty gas. They help operators prevent the gas stream from getting too hot and damaging the scrubbing vessel. Many scrubbing vessels are made of fiberglass reinforced plastics (FRP) or have corrosion resistant liners and only have maximum temperature limits between 200 and 400°F.¹ Some scrubbing systems are equipped with emergency flush systems to prevent damage to the scrubbing vessel in the event of an emergency shutdown or accidental rise in gas stream temperature.

Temperature Limitations

600 SCRUBBERS

Gas temperature monitors on the outlet of a scrubbing device are also used to protect equipment. Temperature gauges for the outlet gas stream help prevent damage to fans downstream of the scrubber. Outlet temperature gauges are also an indicator of scrubber performance. Excesses in the scrubber outlet gas stream temperature can occur from pump failure, pipe blockage, pipe freezing, or pipe breakage.

Static pressure drop

Static pressure gauges may be simple manometers or Magnahelic® gauges, or more complicated electronic instruments that continuously send the static pressure data to a control room. Manometers and Magnahelic® gauges tend to be used on small systems, and electronic systems tend to be used on large scrubbers. Scrubber static pressure gauges are mainly used to monitor performance.

Static pressure gauges across demisters help indicate when excessive solids may be building up on the demister. An excessive solids buildup could lead to droplet reentrainment and fan problems. The pressure gauges help indicate when a wash cycle of the demister should be performed.

Liquid pressure

Liquid pressure gauges in a scrubber are used on supply headers where scrubbing liquid is sprayed. Liquid pressure gauges help indicate when there is a problem with supply headers, such as plugged nozzles, orifice erosion, or header pluggage. A higher than normal pressure reading may indicate pluggage.

Liquid flow

Gauges for measuring liquid flow rates help make sure that gas to liquid ratios, purge streams, and other streams stay within proper limits. For measuring the flow of clean liquid streams, orifice meters, swinging vane meters and rotameters can be used.¹ Liquids with a moderate solids content can be measured with magnetic flow meters or ultrasonic meters.¹

Liquid pH

Instruments for monitoring the pH of the scrubbing liquid are used to control the alkaline feed. The pH is maintained between 5 and 9. If it gets too low (acidic) the scrubbing system components may corrode, but if it gets too high,

deposits of magnesium and calcium precipitates may form in the system. This could lead to scale deposits in piping, demisters, nozzles and walls of the scrubber. Severe deposits of scale can plug equipment.

610 CHOOSING NEW SCRUBBERS FOR INDUSTRIAL PROCESSES

There are three main methods used to evaluate the type of scrubbing design required for a new system. The three methods include an empirical evaluation, pilot scale tests, and theoretical penetration models.¹

610.1 EMPIRICAL EVALUATION

The empirical method of choosing a scrubber design is done by using previous data from systems similar to the new system requiring a scrubber. Most scrubber manufacturers have extensive data regarding the performance of their various commercial brands of scrubbers on different processes. The manufacturer can use his data to decide what scrubber system will best meet the performance requirements of the purchaser. Besides historical performance data, site specific data is used to help determine the best system.¹ The following is a list of the site specific data that may be used:

- Particle size distribution (when available),
- Emission test data (when available),
- Area available for scrubber and waste water treatment,
- Availability of makeup water,
- Type of process,
- Average and maximum gas flow rates,
- Average and maximum inlet gas temperatures,
- Concentrations of corrosive materials in the gas stream (HCl, HF, H₂SO₄),
- Concentrations of potentially explosive material in the gas stream,
- Purge liquid treatment and disposal requirements,
- Alkali supply requirements, and
- Source operating schedule.

600 SCRUBBERS

The first item listed, particle size distribution, is the most important, but it is often unknown. Scrubbing systems are good for handling explosive gas streams. In this area scrubbers are much better control devices than baghouses or electrostatic precipitators. Scrubbers are also good for systems that require an operating schedule with relatively frequent starting and stopping. Scrubbers are also better than baghouses in this area.

The above data is also used to design the components of a scrubbing system and the required pressure drop.

The main advantage with the empirical method is that the scrubber design may be based on actual emissions data, using the same test procedures identical to those applied to a similar existing scrubber.¹ The disadvantage of the empirical method is the inability to account for factors specific to the site that can affect the particle size distribution.¹

610.2 PILOT SCALE TESTS

Pilot scale tests are tests done on small scale scrubbers or models to gain information necessary for a scrubber design. The tests are preferably done on the source that will be controlled so the actual particle size distribution and particle characteristics can be taken into account. If the scrubber is for an entirely new system, a system similar to the one being designed may be used.

Pilot tests are usually conducted by using a small skid-mounted scrubber that can handle between 500 and 2000 acfm. A small amount of the dirty gas stream is diverted from a process for the test.

The advantage of using pilot tests is that a model scrubber similar to the proposed unit can be evaluated on the actual gas stream the new scrubber will control. A number of tests can be done relatively quickly to identify the best pressure drop and other operating conditions. The main disadvantage with pilot testing is that it is expensive. Furthermore, pilot tests usually indicate slightly higher particle removal efficiencies than can be achieved in the full scale scrubber. Non-ideal gas flow conditions in the full scale scrubber are more significant than in a model.¹ The particle size distribution from the model may end up being different than the size distribution in the full size scrubber.

This can occur from errors in the way the gas stream for the model is drawn from the main duct of the process, and changes to the gas stream while the gas flows down the temporary ducting to the pilot scrubber.

610.3 THEORETICAL PENETRATION MODELS

Penetration models are complicated equations that attempt to predict emission rates as a function of particle size. The equations attempt to take into account impaction and diffusion, based on general particle and droplet movement expected in each type of scrubber. Another name for an emission rate from a scrubber used in the application of the equations is "penetration value." Penetration versus particle size data from the equations can be applied to the particle size distribution of a system to estimate the overall emission rate at specific operating conditions.¹ Penetration equations have been derived for a variety of scrubber designs. Some of these equations are presented in The Scrubber Handbook by Calvert, S.J.; Goldschimid, D. Leith and D. Mehta (see reference 19).

When results of the model are compared with actual scrubber emissions in the submicron range, the model predicts slightly higher emissions. This is probably due to the exclusion of diffusion collection mechanisms. Emissions from a scrubber for particles greater than 1 micron is larger than emissions predicted by the model. This may be due to non-ideal flow conditions such as maldistribution.

611 FLUE GAS DESULFURIZATION

Flue gas desulfurization is the use of scrubbers to remove sulfur dioxide (SO_2) from the flue gas (exhaust), primarily from fossil fuel fired power plants. Coal is a fossil fuel that usually requires flue gas desulfurization (FGD) and oil burning power plants may often require it too, depending on the sulfur content of the fuel. Natural gas is a much cleaner fuel, but it can also contain sulfurous compounds.

600 SCRUBBERS

Main Types of FGD Systems

It is important to prevent the emissions of SO_2 (also known as SO_x , includes SO_2 , SO_3 etc.) to the atmosphere because sulfur dioxide is a pollutant that has adverse health effects and causes acid rain and damage to the environment. In California, problems with sulfur dioxide emissions are not as large as the problems with other pollutants such as ozone and particulate matter. Problems with sulfur dioxide are worse on the East Coast where more coal, oil and heating oil are burned.

There are four main families of FGD systems and these include: wet slurry throwaway scrubbing, wet solution throwaway scrubbing, wet sulfur producing scrubbing, and dry scrubbing.¹⁴ Practically all scrubbers are wet scrubbers; few dry scrubbers are in operation.

In wet scrubbers chemical reagents are mixed with the water and used in the scrubber. The reagents are usually an alkali material such as calcium in the form of lime or limestone, or sodium in the form of minerals such as nahcolite or trona. Sulfur dioxide is absorbed by the scrubbing liquid in the scrubber and the chemicals in the water react with the sulfur dioxide producing sulfite and sulfate compounds. The scrubbing liquid which contains the sulfur dioxide falls to the bottom of the scrubber and enters a holding tank where chemical reactions continue to form solids from the sulfur dioxide. The solution may be disposed of or it may be sent to a chemical plant where sulfuric acid or elemental sulfur is produced. In some systems some of the absorbent liquid may be treated and sprayed again in the scrubber.

The cleaned flue gas, which rises out of the stack, is saturated with water and may be acidic. In order to prevent condensation of acids within the stack and possible corrosion problems, the stack gas may be heated.

If a chemical reagent is water soluble, the system is a wet solution FGD scrubbing system. If the reagent is not water soluble, then the system is a wet slurry scrubbing system. Wet solution systems are easier to operate and maintain, but wet solution systems can produce water soluble waste which can pose a greater problem with ground water contamination.

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

611.1 WET SLURRY THROWAWAY SCRUBBING

Wet slurry throwaway scrubbing is the most popular type of FGD system. Most of these scrubbers use a lime or limestone type of reagent. Most of these systems are designed to remove between 85 to 95% of the SO_2 in flue gas.

The lime and limestone type of FGD scrubbers have relatively low capital, operating and maintenance costs. On the other hand, these systems have waste sludge problems. Large amounts of calcium sulfate, calcium sulfite and unreacted lime or limestone and water are produced. The waste must be treated before being sent to a landfill. Deposits and scale can form in the scrubber system and plug equipment. Lime and limestone reagents can only be used one time.

Magnesium-Enriched Lime and Limestone Scrubbing

This system uses magnesium to react with sulfur dioxide instead of just calcium as in the regular lime and limestone scrubber. The products from the absorption and chemical reaction with sulfur dioxide within the scrubber are primarily magnesium sulfite (MgSO_3) and magnesium sulfate (MgSO_4). These products are more soluble, so more sulfur dioxide can be absorbed without increasing scale problems. On the other hand, magnesium enriched lime is more expensive than regular lime.

Lime or Limestone Scrubbing with Adipic Acid

Adipic acid is an organic acid that is used in the nylon industry and as a food additive.¹⁴ Adipic acid reduces the formation of scale in the scrubber, increases absorption efficiency and helps control the pH of the scrubbing liquid. A problem with this system is possible odor problems from decomposition of the acid.

Alkaline Fly Ash Scrubbing

This system differs from the previous ones in that an outside calcium reagent is not the only substance used to perform the absorption. This system uses alkali material from the fly ash of the combustion process. Fly ash particulates are removed from the flue gas with an electrostatic precipitator and put into a holding tank with water to produce the absorbent. This system works well for power plants using low sulfur western coal.

600 SCRUBBERS

611.2 WET SOLUTION THROWAWAY SCRUBBING

Wet solution throwaway scrubbers use a reagent that dissolves in water, producing products from reacted sulfur dioxide that are soluble in water, unlike the slurry type of FGD scrubber. By using a reagent that is soluble with water, scaling and plugging problems are reduced. On the other hand, water soluble reagents are generally more expensive.

Aqueous Sodium Carbonate Scrubbers

This type of system uses a naturally occurring compound called "trona," which is an acidic sodium carbonate which can absorb and react with sulfur dioxide. The aqueous sodium carbonate system mainly differs from slurry type systems in the recirculation and disposal part of the operation. Once liquid has passed through the scrubber it is acidic and is neutralized with alkaline solids. Some of the used scrubbing liquid is drained off with the alkaline solids and sent to the disposal system. Water and sodium carbonate are added to the remaining scrubbing liquid and it is again sent through the scrubber.

Dual-Alkali Scrubbers

In the dual-alkali process an alkali is used in the scrubber, and another one is used in the holding tank. This process combines elements of the lime and limestone process and the aqueous sodium carbonate process.¹⁴ The alkalis that are used to absorb and react with sulfur dioxide are sodium hydroxide or sodium sulfite. These substances are mixed with the water before being sprayed in the scrubber. Once the sulfur dioxide is absorbed, it reacts with the alkalis, producing soluble sodium sulfate. When the scrubbing liquid enters the holding tank after passing through the scrubber, the second alkali, calcium, is added in the form of lime or limestone. The sodium in the reacted product is replaced by calcium, forming calcium sulfite and calcium sulfate solids.

Since solids are formed outside the scrubber, plugging and scaling is reduced. The waste produced by this system is less polluting than the aqueous sodium carbonate scrubber, since it is less likely to dissolve into ground water.

611.3 SULFUR PRODUCING SCRUBBING SYSTEMS

These systems use complex, expensive equipment to produce saleable sulfuric acid or elemental sulfur, and to regenerate reagents for absorbing and removing sulfur dioxide.

Wellman-Lord Scrubbing System

This system uses an absorbent solution of water and sodium sulfite. After the scrubbing process some of the absorbent is thrown away as waste, and the rest is heated to reverse the absorption reaction to produce sulfur dioxide and regenerated sodium sulfite. The sulfur dioxide and sodium sulfite are separated and the sulfur dioxide is sent to a sulfur plant to make sulfuric acid or elemental sulfur. Sodium sulfite is redissolved in water and sodium is added to replace the sodium that was lost in the wastewater.¹⁴ Sodium sulfite is then sent back to the scrubber. For more information on the Wellman-Lord process and sulfur plants, see the Petroleum Refining Technical Manual.

611.4 DRY SCRUBBING

Dry scrubbing is any scrubbing process that produces wastes with less than 5% water. The main types of dry scrubbing include spray drying, dry injection or a combination of the two. The main advantages of dry scrubbing are lower operational, maintenance, and capital costs; reduced waste disposal problems; and reduced plugging, scaling and maintenance.¹⁴ Dry scrubbing can also be used to remove other acid gases besides sulfur dioxide.

Spray Drying

As flue gas flows through a scrubber, a fine mist of dissolved and partially dissolved alkalis is sprayed in the scrubber. Lime is the common alkali material used for the process. Enough moisture is added in the process to partially saturate the flue gas, but the amount of moisture is kept low enough so that the final product remains dry. The lime slurry absorbs and reacts with the sulfur dioxide and heads to another particulate control device. Since the flue gas is hot, the slurry is completely dry when it reaches the second control device, which is an electrostatic precipitator or a baghouse. The solids are then removed and disposed of.

A baghouse used in a dry scrubbing system must be specifically designed for the process. The bags in a baghouse that were not designed for a dry scrubbing system may bind or clog.

600 SCRUBBERS

Dry Injection

In a dry injection system, there is no need for a scrubber. A dry adsorbent is injected into the gas stream. Sodium bicarbonate is usually the type of alkali adsorbent material used. This is an adsorption process since the acid gas is being attached to a solid surface (as opposed to an absorption which is used in all the other wet scrubbers for FGD). As with the spray dryer system, a baghouse or electrostatic precipitator is used to remove the dry material. Most of the reaction that removes sulfur dioxide occurs in the control device, on the bags of the baghouse, so reagent may even be added at the control device.

612 RULE DISCUSSION

Federal EPA

Air pollution regulations exist at the federal level from the Environmental Protection Agency (EPA) in the New Source Performance Standards (NSPS). State laws and statutes applicable to air pollution are in the California Health and Safety Code. Specific state regulations regarding air pollution are developed by the California Air Resources Board and are included in the California Code of Regulations (CCR). Scrubbers are a stationary source and Title 17 contains stationary source regulations. Applicable Health and Safety Code requirements are in Appendix B.

State ARB

Local APCD AQMD

Local air pollution control districts (APCDs) and multi-county air quality management districts (AQMDs) have primary authority and responsibility for enforcing air pollution regulations for stationary sources. Districts regulate with their rules and by issuing Permits to Operate to companies owning or operating pollution generating or control equipment. Districts can also enforce the EPA rules. Many of the district regulations are similar to the EPA's, but in some cases district regulations are more stringent than the EPA's. District regulations cannot be less stringent than the EPA's.

612.1 NSPS

The Federal Clean Air Act requires the EPA to establish new source performance standards for categories of sources which significantly contribute to air pollution. The NSPS apply both to new sources and to modifications to existing sources. The Clean Air Act directly prohibits operation of sources in violation of the NSPS. EPA has the authority to delegate enforcement to the

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

states and has delegated primary authority to several local districts in California. The New Source Performance Standards are located in the Code of Federal Regulations Title 40 Part 60 (40 CFR 60). The NSPS contains subparts ranging from A to VVV that give standards for a multitude of different processes. Some of these processes have particle emission limits, gaseous emission limits, and other limitations that can apply to scrubbers.

40 CFR 60

612.2 DISTRICT REGULATIONS AND PERMITS

Scrubbers are primarily subject to the following regulatory requirements:

1. Air pollution regulations. Most air pollution regulations regarding scrubbers are applicable with the following areas:

- Visible emissions
- Particulate matter emissions
- Fugitive dust emissions
- Gaseous emissions

2. Permits to Operate.

612.2.1 Visible Emissions

All of the local air pollution control districts in California have a visible emissions prohibitory rule. These rules vary in wording, but in almost all cases they express the following:

"... no person shall discharge into the atmosphere from any source whatsoever any contaminant, other than uncombined water vapor, for a period or periods aggregating more than three minutes in any one hour which is:

(a) As dark or darker in shade as that designated as No. 1 (or 20% opacity) on the Ringelmann Chart, as published by the United States Bureau of Mines,

(b) Or of such opacity as to obscure an observer's view to a degree equal to or greater than does smoke described in subdivision (a)."

**Ringelmann
Chart**

600 SCRUBBERS

The State standard for visible emissions (Section 41701, California Health and Safety Code) is No.2 on the Ringelmann Chart, or 40% opacity.

The Ringelmann Chart is a device used for determining whether emissions of smoke are within established limits or standards of permissibility (statutes and ordinances) with reference to the Ringelmann Chart. Smoke density in a plume is compared with a series of graduated shades of gray to black on the Ringelmann Chart, and the smoke density is thus judged by the viewer. Many districts use a more restrictive limit of Ringelmann 1 or 20% opacity (See Table 612.1). EPA Reference Method 9 describes in detail how such visible emissions evaluations should be properly performed, and how to be certified to perform them.

| Table 612.1 Relationship Between Light Transmission, Ringelmann and Opacity | | |
|--|------------|---------|
| % Light Transmission | Ringelmann | Opacity |
| 0 | 5 | 100 |
| 20 | 4 | 80 |
| 40 | 3 | 60 |
| 60 | 2 | 40 |
| 80 | 1 | 20 |
| 100 | 0 | 0 |

The Compliance Division of the ARB trains and certifies government and industry personnel in visible emissions evaluations at its popular "Fundamentals of Enforcement" class which is offered four times a year. Certified personnel are required to recertify every six months in order to demonstrate ongoing evaluation skill.

When reducing the data, the inspector should aggregate the readings taken at 15-second time intervals where the opacity was observed to exceed the Ringelmann limit. Every aggregate of over three minutes of such readings,

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

made in a one hour period, constitutes a violation. This data reduction method reflects the visible emissions limitation in California Health and Safety Code (H&SC) Section 41701. Note that this procedure of data reduction results in more stringent emissions limitations than the Federal method as stated in Method 9. According to Method 9, opacity is determined as an average of 24 consecutive observations recorded at 15-second intervals (i.e., six consecutive minutes of readings, averaged).

Since scrubbers release water vapor, and water vapor is exempt from visible emissions, a visible emissions evaluation must be conducted after the dissipation of the vapor plume. In general, scrubbers should have little or no visible emissions after the water vapor plume.

Visible emissions are important for determining compliance of emissions from a cyclone, but cyclones can also emit water vapor plumes.

612.2.2 Particulate Matter Emissions Limits

Air pollution control districts have either a general particulate-matter-by-concentration rule or a general solid-particulate-matter-by-weight rule. Some districts have both rules. Such rules apply to any source operation which emits or may emit dust, fumes, or total suspended particulate matter.

A concentration rule puts limitations on the maximum concentration of particulate matter allowed to be emitted, based on the volume flow rate of gas discharged, calculated as dry gas at standard conditions. The rule may specify a maximum allowable particulate matter concentration, such as "0.1 grains per cubic foot of gas at dry standard condition," for any stack volume discharge, or the rule may provide a table of varying maximum particulate matter concentrations which are dependent upon the volume flow rate of gas discharged (Table 612.2). In rules with a table of limits, as the volume flow rate discharged increases, the maximum particulate matter concentration allowed decreases (Table 612.3). Refer to district rules for specific requirements.

A solid-particulate-matter-by-weight rule limits the maximum discharge rate allowed for solid particulate matter (aggregate weight discharged from all points of a process in one hour) based on the process rate (weight per hour, usually kilograms or pounds per hour). In general a table is included with the

600 SCRUBBERS

| Table 612.2 Particulate Matter - Concentration | | |
|---|-------|---|
| District | Rule | Limits |
| BAAQMD | 6-310 | 343 milligrams (mg) per dry standard cubic meter (dscm) (0.15 gr. per dry standard cubic foot (dscf)) |
| SCAQMD | 404b | 450 mg per dscm (0.196 grains per dscf) |

maximum allowable particulate matter emission rates, which is dependent on process weight rates (both in kilograms or pounds per hour). Process weight is generally defined as "total weight of all materials introduced into any specific operation, which operation may cause any discharge into the atmosphere." Solid fuels used for combustion are considered as part of the process weight, but liquid and gaseous fuels are not. The process weight is derived by dividing the total process weight by the number of hours in one (1) complete cycle of operation from the beginning of any given process to the completion thereof, excluding any time during which the equipment is idle.

As the process weight increases, the maximum discharge rate also increases. Emissions are averaged over one complete cycle of operation or one hour, whichever is the lesser time period (Table 612.4).

Source tests must usually be conducted to verify compliance with rules for particulate matter emission rates. ARB Method 5 is used in most districts to source test a facility to determine particulate emissions. The federal method for determining emissions is EPA Method 5. EPA Method 5 is located in the Code of Federal Regulations, Title 40, Part 60 (40 CFR 60), Appendix A. The ARB and EPA method 5's are very similar, but the ARB method is more stringent in that it may show higher emissions.

**Table 612.3 (SCAQMD Rule 404) Maximum Concentration of Particulate Matter
Allowed in Discharged Gas Calculated as Dry Gas at Standard Conditions.**

| Volume Discharged | | Maximum Concentration of Particulate Allowed | | Volume Discharged | | Maximum Concentration of Particulate Allowed | |
|----------------------------|--------------------------|---|--------------------------|----------------------------|--------------------------|---|--------------------------|
| Cubic meters per minute | Cubic feet per minute | Milligrams per cubic meter | Grains per cubic foot | Cubic meters per minute | Cubic feet per minute | Milligrams per cubic meter | Grains per cubic foot |
| 25 or less | 883 or less | 450 | 0.196 | 900 | 31780 | 118 | 0.0515 |
| 30 | 1059 | 420 | 0.183 | 1000 | 35310 | 113 | 0.0493 |
| 35 | 1236 | 397 | 0.173 | 1100 | 38850 | 109 | 0.0476 |
| 40 | 1413 | 377 | 0.165 | 1200 | 42380 | 106 | 0.0463 |
| 45 | 1589 | 361 | 0.158 | 1300 | 45910 | 102 | 0.0445 |
| 50 | 1766 | 347 | 0.152 | 1400 | 49440 | 100 | 0.0437 |
| 60 | 2119 | 324 | 0.141 | 1500 | 52970 | 97 | 0.0424 |
| 70 | 2472 | 306 | 0.134 | 1750 | 61800 | 92 | 0.0402 |
| 80 | 2825 | 291 | 0.127 | 2000 | 70630 | 87 | 0.038 |
| 90 | 3178 | 279 | 0.122 | 2250 | 79460 | 83 | 0.0362 |
| 100 | 3531 | 267 | 0.117 | 2500 | 88290 | 80 | 0.0349 |
| 125 | 4414 | 246 | 0.107 | 3000 | 105900 | 75 | 0.0327 |
| 150 | 5279 | 230 | 0.1 | 4000 | 141300 | 67 | 0.0293 |
| 175 | 6180 | 217 | 0.0947 | 5000 | 176600 | 62 | 0.0271 |
| 200 | 7063 | 206 | 0.09 | 6000 | 211900 | 58 | 0.0253 |
| 250 | 8829 | 190 | 0.083 | 8000 | 282500 | 52 | 0.0227 |
| 300 | 10590 | 177 | 0.0773 | 10000 | 353100 | 48 | 0.021 |
| 350 | 12360 | 167 | 0.073 | 15000 | 529700 | 41 | 0.0179 |
| 400 | 14130 | 159 | 0.0694 | 20000 | 706300 | 37 | 0.0162 |
| 450 | 15890 | 152 | 0.0664 | 25000 | 882900 | 34 | 0.0148 |
| 500 | 17660 | 146 | 0.0637 | 30000 | 1059000 | 32 | 0.014 |
| 600 | 21190 | 137 | 0.0598 | 40000 | 1413000 | 28 | 0.0122 |
| 700 | 24720 | 129 | 0.0563 | 50000 | 1766000 | 26 | 0.0114 |
| 800 | 28250 | 123 | 0.0537 | 70000 or more | 2472000 | 23 | 0.01 |

Table 612.4 (SCAQMD Rule 405)**Maximum Discharge Rate of Particulate Matter (Aggregate Discharged from All Points of Process)**

| Process Weight per hour | | Particulate Discharge Rate | | Process Weight per hour | | Particulate Discharge Rate | |
|-------------------------|-----------------|----------------------------|-----------------|-------------------------|-----------------|----------------------------|-----------------|
| Kilograms per hour | Pounds per hour | Kilograms per hour | Pounds per hour | Kilograms per hour | Pounds per hour | Kilograms per hour | Pounds per hour |
| 100 or less | 220 or less | 0.45 | 0.99 | 9000 | 19840 | 5.308 | 11.7 |
| 150 | 331 | 0.585 | 1.29 | 10000 | 22050 | 5.44 | 12 |
| 200 | 441 | 0.703 | 1.55 | 12500 | 27560 | 5.732 | 12.6 |
| 250 | 551 | 0.804 | 1.77 | 15000 | 33070 | 5.982 | 13.2 |
| 300 | 661 | 0.897 | 1.98 | 17500 | 38580 | 6.202 | 13.7 |
| 400 | 882 | 1.053 | 2.34 | 20000 | 44090 | 6.399 | 14.1 |
| 500 | 1102 | 1.209 | 2.67 | 25000 | 55120 | 6.743 | 14.9 |
| 600 | 1323 | 1.34 | 2.95 | 30000 | 66140 | 7.037 | 15.5 |
| 700 | 1543 | 1.461 | 3.22 | 40000 | 88180 | 7.527 | 16.6 |
| 800 | 1764 | 1.573 | 3.47 | 50000 | 110200 | 7.931 | 17.5 |
| 900 | 1984 | 1.678 | 3.7 | 60000 | 132300 | 8.277 | 18.2 |
| 1000 | 2205 | 1.777 | 3.92 | 70000 | 154300 | 8.582 | 18.9 |
| 1250 | 2756 | 2.003 | 4.42 | 80000 | 176400 | 8.854 | 19.5 |
| 1500 | 3307 | 2.206 | 4.86 | 90000 | 198400 | 9.102 | 20.1 |
| 1750 | 3858 | 2.392 | 5.27 | 100000 | 220500 | 9.329 | 20.6 |
| 2000 | 4409 | 2.563 | 5.65 | 125000 | 275600 | 9.83 | 21.7 |
| 2250 | 4960 | 2.723 | 6 | 150000 | 330700 | 10.26 | 22.6 |
| 2500 | 5512 | 2.874 | 6.34 | 175000 | 385800 | 10.64 | 23.5 |
| 2750 | 6063 | 3.016 | 6.65 | 200000 | 440900 | 10.97 | 24.2 |
| 3000 | 6614 | 3.151 | 6.95 | 225000 | 496000 | 11.28 | 24.9 |
| 3250 | 7165 | 3.28 | 7.23 | 250000 | 551200 | 11.56 | 25.5 |
| 3500 | 7716 | 3.404 | 7.5 | 275000 | 606300 | 11.82 | 26.1 |
| 4000 | 8818 | 3.637 | 8.02 | 300000 | 661400 | 12.07 | 26.6 |
| 4500 | 9921 | 3.855 | 8.5 | 325000 | 716500 | 12.3 | 27.1 |
| 5000 | 11020 | 4.059 | 8.95 | 350000 | 771600 | 12.51 | 27.6 |
| 6000 | 13230 | 4.434 | 9.78 | 400000 | 881800 | 12.91 | 28.5 |
| 7000 | 15430 | 4.775 | 10.5 | 450000 | 992100 | 13.27 | 29.3 |
| 8000 | 17640 | 5.089 | 11.2 | 500000+ | 1102000+ | 13.6 | 30.0 |

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

612.2.3 Gaseous Emissions

Sulfur

All districts limit the concentration of sulfur dioxide (SO_2) which may be discharged into the atmosphere. Rules for sulfur compound emissions exist for different processes, such as sulfur recovery plants, sulfuric acid plants, fluid catalytic cracking units, cokers, and fuel burning equipment. Table 612.5 illustrates some general standards in sulfur dioxide rules. Refer to district rules for specific requirements.

Some sulfur rules limit the stack discharge concentration to a specified ppm from any combustion operation. Other rules require that a process not emit enough sulfur compounds to exceed the state or federal standards at the ground level (0.05 ppm, by volume, for 24 hours average, or 0.25 ppm, by volume, for 1 hour average).

Some districts also limit the quantity of sulfur emissions based on weight in a fuel burning rule, fuel burning equipment rule or sulfur content of fuels rule. Districts may also limit sulfur emissions by pounds of sulfur dioxide per hour of operation, or grains (grams) of sulfur dioxide per cubic foot (cubic meter) of flue gas.

Rules for hydrogen sulfide (H_2S) may limit emissions by a stack discharge limit of 10 ppm, by volume. Districts may also limit H_2S by ground level concentration, i.e. 0.03 ppm over one hour.

NOx

Some districts limit NOx in fuel burning equipment rules. These limit the concentration of NOx in flue gas from stationary sources by the heat input of the device. Some example of heat input rates used in rules include 250 million Btu/hr, 1.75 billion Btu/hr, etc. (Table 612.6).

Some districts have rules that limit NOx by weight from fuel burning equipment. A limit used by some districts, for example, is around 140 pounds per hour, calculated as nitrogen dioxide (NO_2). Some units are equipped with continuous emission monitors for NOx, but NOx emissions usually must be determined with sources tests. Table 612.6 illustrates general NOx emission limits. Refer to district rules for specific requirements.

Hydrogen Sulfide Limits

600 SCRUBBERS

| Table 612.5 District Regulations for Sulfur Compounds | | |
|--|------------|---|
| District | Regulation | Limit |
| BAAQMD | 9-1-301 | No emissions that result in ground level concentrations greater than: .05 ppmv for 24 hr. avg. .25 ppmv for 1 hr. avg. |
| BAAQMD | 9-1-302 | No emissions of sulfur dioxide greater than 300 ppm (dry). (Does not apply to ships, sulfur recovery plants, sulfuric acid plants, FCCs) |
| SCAQMD | 468a | No emissions of sulfur compounds expressed as SO ₂ over 500 ppm, calculated as dry, averaged over 15 min. (applies to all sulfur recovery units) |
| SCAQMD | 468c | No emissions of sulfur compounds expressed as SO ₂ over 198.5 lbs (90 kg) per hour (applies to all sulfur recovery units). |

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

Table 612.6
District Regulation for Nitrogen Oxides

| District | Regulation | Limit | | |
|----------|-------------------|--|---|--|
| BAAQMD | 9-3-301 | Max. input rate (Btu/hr) | Fuel type | Max. emissions (ppm) |
| | | 1.75 billion | gaseous | 175 |
| | | | liquid | 300 |
| BAAQMD | 9-3-303 | 250 million (heaters built or modified after 4/19/75) | gaseous | 125 |
| | | | liquid | 225 |
| SCAQMD | 1146 c,1 | No emissions expressed as NO ₂ more than the following: | | |
| | | Max. input capacity (million Btu/hr) | Rated annual heat input (Btu/year) | Max. emissions (ppm) (gaseous, liquid and solid fuels) |
| | | 5 or greater | over 9,000,000,000 | 40 (0.05 lb/million Btu) |
| | | 40 or greater | greater than 25 % annual capacity factor | 30 |
| | | 40 or greater | equal to or less than 25 % annual capacity factor | 40 |
| SCAQMD | 2000 through 2015 | Rule 1146 will be replaced by RECLAIM rules for some facilities. | | |

600 SCRUBBERS

Odors

Odors can be sources of public nuisances. Most districts use the Health and Safety Code Section 41700 to determine public nuisances. It states:

"Except as otherwise provided in section 41705, [agricultural exemptions] no person shall discharge from any source whatsoever such quantities of air contaminants or other material which cause injury, detriment, nuisance, or annoyance to any considerable number of persons or to the public, or which endanger the comfort, repose, health, or safety of any such persons or the public, or which cause, or have a natural tendency to cause, injury or damage to business or property."

The Bay Area Air Quality Management District also has a rule regarding odors (Regulation 7-300). This rule limits the amount of odorous substances discharged in the air by the amount of dilution by odor free air required and the amount of discharge that occurs. The regulation also limits emission concentrations by ppm for dimethylsulfide, ammonia, mercaptans, phenolic compounds, and trimethylamine.

612.2.4 Permits

Under the authority of the California Health and Safety Code, and in order to comply with the California State Implementation Plan and New Source Performance Standards where applicable, the districts issue Permits to Operate which contain conditions for the operation of industrial processes and emission control equipment. The conditions in Permits generally reflect the requirements of district rules that apply to a source.

Facilities must function within the parameters stated in the Permit to Operate issued by the district. Permits must be posted on the equipment, where applicable, and they must be current. If these conditions are not adhered to, it is a violation.

Permits have an equipment list which lists the equipment covered by it. It is a violation to operate pollution generating or control equipment that is not Permitted. It is also a violation to make modifications to Permitted equipment without district approval. When new equipment or modifications are required, a district will issue an Authority to Construct to the owner or operator of the equipment.

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

Whenever a company must make a modification to its equipment or buy new equipment, it should notify its local district immediately. A district can usually accommodate a source even when modifications must be made in a short period of time.

An Authority to Construct will list the equipment to which it applies and it will list conditions similar to those on a Permit to Operate. After the new equipment is modified or constructed the district may conduct a source test and issue a Permit to Operate.

Authority to Construct

Some typical conditions stated on a Permit to Operate include:

Permit Conditions

1. Limits on scrubber inlet and outlet temperatures
2. Limits on scrubber pressure drop.
3. Limits on liquid pH.
4. Recordkeeping requirements.
5. Requirements for continuous emission monitors.
6. Emission limits for NO_x, SO_x, particulate matter.
7. Limits on fuel usage (Btu/day, gal/day) and the type of fuel for the process (for scrubbers cleaning flue gas).
8. Throughput limits.
9. Limits on solids content of the scrubbing liquid.
10. Limits on the minimum water input rate.

600 SCRUBBERS

613 INSPECTION INTRODUCTION

Scrubbing systems are inspected in order to verify that a company's equipment is designed and operated in accordance with air pollution regulations and Permits to Operate. There are four ways that the compliance status of a source can be evaluated:

1. Engineering evaluations
2. Inspections
3. Source testing
4. Continuous emission monitoring

Of these, only the first and the third provide actual emission data as to the extent of emissions from a facility. Inspections will primarily be the focus of this section, but source testing and continuous emission monitoring shall be briefly discussed.

Inspections of scrubbing systems may be performed for any one of the following reasons:

1. Compliance determination
2. Complaint investigation as a result of excess emissions or equipment malfunction
3. Source plan approval
4. Review or renewal of Permits
5. Special studies

Examples of special studies would be operating and maintenance evaluations, or updating emission inventories.

Compliance-type inspections only provide preliminary emissions assessments. Source testing is the method of determining compliance with an emission standard. Compliance inspections are usually unannounced so that a facility can be evaluated under normal operating conditions.

For other inspections pertaining to source construction, plan approval, Permits to Operate, or "baseline type" inspections, the plant should be given sufficient advance notice so that qualified plant personnel can be present to provide the drawings, manuals, and process information that may be required. Prior notice

Reasons for Inspection

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

should also be given when performing inspections for special studies designed to document operating and maintenance practices, or process and emission data. This will allow the operator time to make readily available information such as raw material rates, production levels, and stack test results. Regardless of the type of inspection to be conducted, pertinent supporting information should be obtained prior to, during, and following the source evaluation.

One of the best ways a source can stay in compliance with air pollution regulations is through preventative maintenance inspections. Companies that have efficient inspection and maintenance (I&M) programs tend to have fewer breakdowns, require fewer variances, have less down time and can save money. With an efficient I & M program, problems with equipment can be anticipated and surprising catastrophic failures can be reduced. A good I & M program also requires that neat, orderly, consistent records of self-inspections are kept by the company. Local districts can usually assist sources with I & M programs.

I & M

613.1 SEQUENCE OF INSPECTION

The sequence of an inspection is a question of the order which to inspect the equipment in a scrubbing system. The two main logical sequences to follow are a co-current and a counter-flow approach, but regardless of the type of sequence chosen, it is usually best to first inspect the outside of a facility. By inspecting the perimeter of a plant, an inspector can see if there are any illegal emissions crossing the plant's boundary before the source is aware of an inspector's presence.

613.1.1 Co-Current Approach

The inspection of a scrubbing system using a co-current approach is conducting the inspection in the same general direction of the flow of the gas stream. The general sequence would be the process, the capture system, the control device, and the stack. An inspector may want to use this type of approach when he is unfamiliar with some process details and would like to observe them before seeing the scrubber. The scrubbing liquid system can also be inspected in the direction of flow, although most of the liquor is recirculated. The inspection would simply start and end at the same piece of equipment.

613.1.2 Counter-Flow Approach

An inspection with a counter-flow sequence is conducted against the direction of gas flow. An inspection of this type would generally begin at the stack and continue to the control device, capture system and then the process. The advantage of this approach is that an inspector may be able to more quickly identify where an emission problem originates. The inspection of the scrubbing liquid system may also be conducted opposite the direction of flow of the liquid.

613.1.3 Other Approaches

In some instances an inspector may not start at the stack or the process or the beginning or end of a system. If observations of possible illegal emissions were made while outside the facility, an inspector may want to head directly to the scrubber or the source of the emission. If an inspector suspects tampering with the scrubber, he may head there directly. If an inspection is a strict, unannounced compliance-type, or if an inspector is very familiar with the process and only has a particular item to deal with, the inspection could start and finish in a different manner.

613.2 LEVELS OF INSPECTION

Four different levels of inspection for scrubber systems have been developed by the U.S. EPA. A level 1 inspection consists of an inspection that is the least in-depth and a level 4 inspection is the most in-depth. The levels are inclusive; a level 3 inspection, for example, would also include all the items done in a level 1 and level 2 inspection. Although these levels may not be always be strictly adhered to in practice, the levels help organize all the means in which a scrubber system can be inspected. In a level 1 inspection, an inspector conducts a visible emissions evaluation outside the facility. In a level 2 inspection, an inspector conducts a walkthrough evaluation of the wet scrubber system and process equipment. All the data acquired in a level 2 inspection is acquired from on-site gauges. In a level 3 inspection, independent measurements of wet scrubber operating conditions separate from the existing on-site gauges are conducted. This is usually done when the existing on-site gauges are inadequate. A level 4 inspection is performed by agency supervisors or senior inspectors to acquire

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

baseline data. As with the level 3 inspection, independent monitoring equipment is used for the level 4 inspection. The "baseline" data acquired in past level 4 inspections is used by inspectors to check the operation of the scrubbing system.

614 PRE-INSPECTION PROCEDURES

It is important to prepare for the scrubber inspection prior to your visit to the facility. Rules and Permits can be very complicated and preparations must be made for a successful inspection. This section is a discussion of some general guidelines on what steps to follow prior to the inspection.

614.1 FILE REVIEW

Prior to the site inspection, the inspector should review all information available in the district source files, including: approved Permits, equipment lists, conditions for each Permit, previous inspection reports, Notices of Violation, breakdown reports, enforcement actions taken, odor complaints, variance histories, alternative emissions control plans, abatement orders, source tests, and the design of the scrubber system.

Verify that all applicable Permit(s) are current and valid. Bring a current copy of the Permit(s) with you and bring extra copies in case the facility has misplaced or lost their copy.

The inspector may wish to complete some portions of the inspection documentation before arriving at the facility, as this will save time during the pre-inspection meeting. If your district has checklists or rule specific forms, use them.

600 SCRUBBERS

614.2 REGULATION REVIEW

You should review any references to the specific rules which are noted in the source files. In particular, be familiar with each standard and exemption in the rules. Discuss particulate regulations with experienced personnel and review any policies your district may have. Make sure that you receive consistent interpretations on how to apply the requirements of rules.

614.3 EQUIPMENT CHECK

Make sure that you have the following equipment available for use during the inspection: vision protection, hearing protection, safety shoes, hard hat, gloves, identification, business cards, pens, wipes, inspection forms, chain of custody forms, sampling cans, can case, labels, and thermometer.

614.4 PRE-ENTRY AND ENTRY

When you arrive at the plant, notice if there are any strong odors. If there are any odors, make sure you document them and plan on finding the sources as soon as possible after entering the facility.

Request to see the previous contact mentioned in the files. Depending on the facility, it may be the environmental coordinator, supervisor, president, maintenance worker or operator. Always present your business credentials immediately to avoid confusion.

If the source is unfamiliar with your district's authority, be prepared to cite and provide copies of California Health & Safety Code (CHSC) Section 41510: Right of Entry (a copy is available in the Appendix). Know and follow your district's policy if the facility refuses entry.

614.5 PRE-INSPECTION MEETING

Before the inspection begins, the inspector should meet with the source representative to obtain operating information. The inspector should state the purpose of the inspection and identify the equipment which will be inspected. Facility information can be verified during this meeting, including: the facility

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

name and ownership, address with city and zip code, contact name, contact title, phone number and area code. Discuss safety procedures and whether or not there have been any odor problems in the past. Request a copy of material safety data sheets (MSDS), and if necessary discuss sampling procedures.

The district's equipment list on the Permit to Operate should be compared to the facility's Permit to Operate. The items should be the same. If they are not, a Notice of Violation may have to be issued. Also, check existing Permit conditions and ask if any other changes have been made to the operation which are not reflected in the Permit.

615 SCRUBBING SYSTEM INSPECTION

Inspectors can determine whether a scrubbing system complies with air pollution regulations and Permits to Operate by obtaining operating information and comparing the data to baseline values and limits on Permits. Although source tests must be conducted to determine the emissions, the items in this section will discuss how to inspect scrubbing equipment to determine compliance.

615.1 SCRUBBER VISIBLE EMISSIONS (ALL LEVELS)

EPA Method 9 (Visual Determination of the Opacity of Emissions from Stationary Sources) is found in 40 CFR Ch. 1, Part 60. The method requires the recording of certain specific information in the field documentation of a visible emission observation. The required information includes the name of the plant, the emission location, the type of facility, the observer's name and affiliation, the date, the time, the estimated distance to the emission location, the approximate wind direction, the estimated wind speed, a description of the sky conditions, the plume background, in addition to a minimum of 24 opacity observations.

In California the visible emission regulation is in Section 41701 of the California Health and Safety Code. The limit in the Health and Safety Code is a Ringelmann No. 2 or 40% opacity. The Ringelmann chart is a gray to black smoke scale published by the United States Bureau of Mines within a ranging from 0 to 5 where "0" is no visible smoke and "5" is totally black 100% opaque

600 SCRUBBERS

smoke (Table 612.1). In most districts the limit is Ringelmann No. 1 or 20% opacity. White or colored smoke is measured by percent opacity. California provides that an aggregate of any of 13 or more readings (totalling more than 3 minutes) taken in a 1-hour period is a violation.

Before entering a facility, the visible emissions from the stack should be observed. A visible emissions observation from scrubbers is more difficult in that the water vapor in the flue gas cannot be counted as part of the plume. Because of the condensed water vapor in scrubber plumes, opacity monitoring equipment is not used in particulate wet scrubbers. Therefore, the emissions from a scrubber must be viewed after the steam plume evaporates or "breaks." There should be little or no visible emissions beyond the evaporation of the steam plume. If the opacity of the plume beyond the vaporization of the steam is greater than 10%, there is a problem with the system. If it is over a Ringelmann 1 it is a violation in most districts. When a detached steam plume forms, it may be possible to evaluate visible emissions between the stack and the steam plume. Excessive emissions could be from a high concentration of vaporous material in the flue gas, or a high concentration of submicron particles.

It may also be good practice to acquire the maximum and minimum short term visible emissions, especially if there are variations in the operating conditions of the industrial process.

615.2 DROPLET REENTRAINMENT

Excessive droplet reentrainment usually indicates a problem with the demister. Check for a rainout of droplets in the immediate vicinity of the stack. A very light rainout of droplets in the air around the stack may be normal, but the ground around the stack should not be wet. Droplet fallout can create a local nuisance.

Check for moisture stains or discoloration on the stack and any adjacent equipment. Look around the top of the stack for the existence of a "mud lip." Stains, discolorations, or a mud lip also may be an indication of a demister problem.

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

615.3 SCRUBBER SYSTEM GENERAL PHYSICAL CONDITIONS (LEVELS 2,3,4)

Walk around the wet scrubber system to familiarize yourself with it. As you walk around the system look for signs of corrosion and erosion. If there is any damage, check for fugitive emission leaks. Look for cracked or worn ductwork expansion joints, sagging piping, pipes that can't be drained or flushed and any excessively vibrating mechanical equipment such as fans or pumps. Corroded or worn equipment is an indication of poor maintenance and possible violations. If any excessively vibrating fans or motors are encountered, leave the area and notify facility personnel immediately. An excessively vibrating machine could be a sign of impending catastrophic failure of equipment.

615.4 SCRUBBER STATIC PRESSURE DROP (LEVELS 2,3,4)

The pressure drop of a scrubber should be simply read from the gauges on the device. For mechanically aided scrubbers the pressure gauges should indicate an increase in pressure.

The pressure gauges on the scrubber should be in good working order. The gauges should be free of deposits and grime. If it seems that the gauge is not working properly, ask personnel to disconnect one of the lines leading to the gauge (if applicable) to see if gauge responds properly. Check the reading with the base line value of the pressure drop (or rise). Table 615.1 illustrates some possible causes of excessively high and low pressure drops in scrubbers.

615.4.1 Level 3 and 4 Inspections

In level 3 and 4 inspections the pressure drop must be measured without the gauges on the control device. First, safe and convenient measurement ports must be located. In a level 4 inspection, these ports would have to be installed with the help of facility personnel (see Preferred Measurement Ports for Air Pollution Control Systems, EPA 340/1-86-034 regarding port installation). Ports may be found by disconnecting existing on-site gauges, but get facility personnel to remove the gauges.

600 SCRUBBERS

Table 615.1
Possible Causes of Low or High Pressure Drops in Some Scrubbers

| Scrubber Type | Typical Pressure Drop (in.) | Possible Cause of Low Static Pressure Drop | Possible Cause of High Static Pressure Drop |
|---------------|-----------------------------|---|---|
| Wet Dynamic | 2-12 | -Low rotational speeds | -High rotational speeds |
| Tray tower | 2-12 | -Low gas flow rates -Collapse of tray(s) -Low liquor flow rates | -High gas flow rates -Partially plugged trays |
| Packed bed | 2-6 | -Low gas flow rates -Collapse of bed | -High gas flow rates -Partially plugged bed |
| Venturi | 10-120 | -Low gas flow rates -Low liquor flow rates -Eroded dampers -Increased venturi throat opening | -High gas flow rates -High liquor flow rates -Decreased venturi throat opening, partially blocked or constricted throat |
| Rod deck | 10-120 | -Low gas flow rates -Low liquor flow rates -Eroded rods -Increased rod spacing | -High gas flow rates -High liquor flow rates -Decreased rod spacing |
| Orifice | 4-25 | -Low gas flow rates -Low liquor levels | -High gas flow rates -High liquor levels |

If the ports are close together, connect the pressure gauge to them and measure the pressure for 1 to 5 minutes. If the ports are far apart, measure the static pressure at one port for 10 to 30 seconds and then measure the static pressure at the other port for the same amount of time. In order to get an accurate reading, the pressure measured at the ports should remain constant. The difference between the two values will yield the pressure drop.

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

615.5 GAS OUTLET TEMPERATURE

Measuring the temperature of the outlet gas flow helps determine if the liquid-gas distribution is poor or if the liquid flow rate is inadequate. Evaluating the temperature of the outlet gas stream is usually part of a level 3 or 4 inspection, because the scrubber equipment usually is not equipped with temperature gauges on the outlet side.

First a convenient, safe port location must be located on the outlet side of the scrubber vessel in the ductwork or even on the scrubber shell. Small ports under 0.25 inches in diameter are sufficient. A grounding cable should be attached to the temperature probe if there is any explosive potential in the gas. The probe should be sealed in the port to prevent air infiltration which can alter the temperature measurement. Allow the probe to stay in the duct several minutes so it will be in equilibrium with the gas. Acquire temperature readings with the probe as close as possible to the center of the duct.

High gas temperatures in excess of 10°F above baseline values may indicate liquid-gas maldistribution or an inadequate liquid flow (liquid to gas ratio too low).

615.6 GAS FLOW RATE

The gas flow rate in a scrubbing system may change due to variations in the process conditions, but there is a range of gas flow rates that each scrubber system should be operated within.

A simple method of evaluating the gas flow rate is by checking the fan motor current. Record the fan motor current and compare it to any Permits conditions for the fan, and, if applicable, acquire copies of relevant fan motor records.

For a level 3 or 4 inspection, the common instrument used to measure the gas flow is a S-type Pitot tube. A safe port location must be located on the duct. U.S. EPA Reference Methods 1 and 2 contain procedures on measuring the gas flow.

**Fan Motor
Current**

600 SCRUBBERS

615.7 LIQUOR INLET PRESSURE (LEVELS 2,3,4)

In most scrubbing systems pressure gauges may be provided, indicating the pressure of the scrubbing liquid in the header that supplies the spray nozzles. Record the reading on the gauge and compare it to the baseline value. If the pressure is lower than the baseline value there may be erosion occurring in or around the nozzles. If the pressure is higher than normal, there may be one or more plugged nozzles.

Pressure gauges for the headers are prone to giving inaccurate readings. The gauges are vulnerable to corrosion and clogging from solids deposits. Other data such as the pump discharge pressure and the outlet gas temperature should be checked to verify a low or high pressure reading.

615.8 LIQUOR TURBIDITY AND SOLIDS SETTLING RATE (LEVELS 2,3,4)

With a clear container, ask facility personnel to acquire a sample of the scrubbing liquor upstream of the scrubber, so the liquid entering the scrubber can be inspected. A sample tap downstream of the recirculation pump may be a good location to acquire a sample.

Carefully observe the liquid in the container immediately after the sample is taken and describe the turbidity as one of the following categories:

Turbidity Categories

1. Clear,
2. Very light,
3. Light,
4. Moderate,
5. Heavy, or
6. Very heavy.

Five minutes after the first observation observe the turbidity again and describe it with the above categories. Also describe the thickness of the solids that have settled at the bottom of the container.

Be careful not to get any of the scrubbing liquid on your skin. Use gloves when handling the container and be careful not to drop it. It could contain toxins and could very acidic or alkaline.

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

615.9 LIQUOR PH (LEVELS 2,3,4)

Locate the pH meter or meters for the scrubbing system; one is usually located in the recirculation tank or on the scrubbing liquor outlet lines from the scrubber. Make sure the meter is working properly by reviewing the calibration records. It may be possible to witness the calibration of the meter. Record the value indicated on the pH meter. If the pH reading on the meter is found to be false, record the reading on the meter and the actual correct pH reading. Check the pH reading(s) with the baseline value or Permit. If the reading is markedly different from the baseline value or Permit, there may be a problem with the equipment and possible violations to document.

Review the records for the pH meter that have been recorded since the last inspection or at least the last month. Acquire a copy of the pH records taken since the last inspection, especially if pH is part of the Permit conditions. Reviewing the records may not be fruitful if the pH meter is not working properly. Check the records with the baseline values or Permit.

If the scrubber has a pH meter on the inlet side and outlet side, the pH indicated on the meters should normally decrease between 0.5 to 2.0 pH units. This is from the absorption of carbon dioxide, sulfur dioxide and other acid gases in the gas stream. All the pH meters should generally read between 5.5 and 10.0.

In a level 3 or 4 inspection, the pH of the scrubbing liquid would also be determined by acquiring a sample and using a portable pH meter. Warm up the pH meter before the sample is acquired by facility personnel. It's best to measure the pH of the liquor sample as soon as possible, since chemical reactions in the liquid could alter its pH. In a level 3 inspection, check the value with the baseline value or Permit.

615.10 SCRUBBER LIQUOR RECIRCULATION RATE (LEVELS 2,3,4)

Check the flow rate of the liquor into the scrubber. A common cause of excess emissions from a scrubber is an inadequate liquor flow rate. The flow meter measuring the recirculation rate is prone to failure. Check the condition of the meter; if it has not been well maintained it is more probable that the reading is

600 SCRUBBERS

inaccurate. It may be possible to check the flow of liquor from the scrubber to the recirculation tank. If this flow is low it also indicates an inadequate liquor flow rate. Record the readings from these flow meters and check them with the baseline value or Permit.

Many small-sized scrubbing systems are not equipped with flow meters, but the flow can still be evaluated. First the discharge pump can be inspected. Check the pump discharge pressure; if it is higher than normal this indicates a lower flow rate. Check the pump motor current; if it is lower than it should be the flow rate is also lower. The temperature of the exiting gas stream can also be checked. Higher temperatures in the exiting gas stream indicate lower flows. Record all the above measurements taken and compare them to Permit and baseline values.

615.11 DEMISTER INSPECTION (LEVELS 2,3,4)

The demister should be inspected, especially if droplet reentrainment has occurred. If the demister has pressure gauges on it record the pressure drop. An excessive pressure drop could mean that the demister is partially plugged. The pressure drop across the demister usually varies between 0.5 to 2.0 inches of water.

It may be possible to observe the demister, especially if the scrubber is off-line. Get permission from facility personnel before opening any access doors and in order to make sure it is safe. Check for a solids buildup and the condition of any spray nozzles. **Never enter any enclosed equipment** at a facility unless all confined space requirements are met. The state and federal safety and health departments (OSHA) have detailed procedures that must be followed to protect personnel from serious injury or death. These procedures are necessary because confined spaces can be filled with toxic gases, oxygen deficient and can contain other hazards. Confined space requirements are defined in the California Code of Regulation, Title 8, Sections 5156-5159 (8 CCR 5156-5159) and in the Code of Federal Regulations, Title 29, Chapter 27, Section 1910.146 (CFR 1910.146).

**Table 615.2
SCRUBBER INSPECTION FORM A**

| <u>Pre-Inspection:</u> | <u>Field Inspection:</u> |
|---|---|
| Facility name: Unit I.D. number: | Date/time: |
| Permit number: Permit expiration date: | Inspector: Agency: |
| Facility address: | Facility contact person(s)/title(s): |
| Date unit was built or last modified: | |
| Scrubber General Physical Conditions | |
| Scrubber type/design: | Any visible emissions beyond the steam plume? Any excessive droplet reentrainment? Is the area around the stack wet? Is there a mud lip? Are there any stains or discolorations on the stack or adjacent equipment? Ductwork condition: Are the joints in the ductwork in good condition? Any holes or gaps in ductwork? |
| Gauges and Monitors | |
| Maximum and minimum scrubber pressure drop: | Pressure drop: |
| Fan rpm range: Fan current range: | Fan rpm: Fan current: |
| Maximum gas outlet temperature: | Gas outlet temperature: |
| Liquor pressure: Liquor flow rate: | Liquor pressure: Liquor flow rate: |

600 SCRUBBERS

| Table 615.3 SCRUBBER INSPECTION FORM B | |
|---|--|
| <u>Pre-Inspection:</u> | <u>Field Inspection:</u> |
| Liquor Turbidity | |
| Permit requirements: | <p>Acquire a scrubbing liquor sample and observe the turbidity. Describe the turbidity as one of the following:</p> <p>clear, very light, moderate, heavy, very heavy</p> <p>Liquor turbidity after 5 minutes:</p> <p>clear, very light, moderate, heavy, very heavy</p> |
| Liquor pH | |
| Maximum pH range: | <p>Location of pH meter:</p> <p>Liquor pH:</p> |
| Scrubber Internal Conditions | |
| Permit requirements: | <p>Is the demister, packing, or tray orifices relatively free of solids build-up?</p> <p>Are the trays in the scrubber sagging?</p> <p>Are any of the spray nozzles plugged?</p> <p>Any excessive corrosion in downcomers, trays or other areas?</p> <p>Are there any broken downcomers?</p> |

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

615.12 INSPECTING THE INSIDE OF PARTICULAR SCRUBBER DESIGNS (LEVELS 2,3,4)

In order to look at the inside of a scrubber for an inspection it must be out of service. Permission must be obtained from facility personnel and access doors or hatches should be opened by operators. Some systems may be equipped with sight glasses to help view the inside. As mentioned above, make sure confined space requirements are met.

Packed Bed Scrubbers

Look at the support for the packing and make sure it is not collapsed, or heavily corroded. Notice if there is any excessive solids accumulation in the bed, especially near the bottom where the dirty gas enters the vessel. If they can be seen, inspect the spray nozzles for erosion or pluggage.

Tray Tower Scrubbers

Check for bowed or sagging trays and look for plugged holes in the trays. Look for corrosion on trays and downcomers. Make sure there are no broken downcomers.

Orifice Scrubbers

Check for excessive solids deposits in the liquor containers, demisters, and at the gas stream entrance. Look for erosion to the inlet of the orifice sections.

Rod Deck Scrubbers

Look for excessive erosion of the rods and pluggage of the spray nozzles.

Venturi Scrubbers

Inspect for erosion of dampers and venturi throats. Check for restricted throat damper movement from solids deposits.

615.13 PROCESS INSPECTION

The processes in which scrubbers are used to control emissions vary widely and the inspection of these processes may be very different, but there are some common items that can be checked.

600 SCRUBBERS

The capture system should be checked for fugitive emissions and effectiveness, especially if the scrubber system pressure drop was found to be high or air infiltration is discovered. Record all applicable process operating rate parameters that illustrate that the process is operating according to Permit requirements. Some of the types of parameters that should be recorded include:

- Gas stream temperatures,
- Gas stream static pressures,
- Gas stream oxygen levels, and
- Raw material characteristics (do materials comply with Permits?).

616 CYCLONE INSPECTION

As with scrubbers, all pre-inspection procedures should be conducted before a cyclone is inspected. Many of the pre-inspection guidelines mentioned for scrubbers can be applied to cyclones. Review Sections 613 and 614 for this information.

616.1 VISIBLE EMISSIONS

A visible emissions evaluation of the cyclone should be conducted. A high opacity may indicate that the cyclone is operating on particles that are smaller than it was designed to handle. Small particles scatter more light than large ones and are more visible. Cyclones can also create a condensing vapor plume, especially when the gas stream is hot. Once the hot gas enters the atmosphere it cools and material in the plume may condense. If the condensing material is water vapor, it is not an illegal visible emission.

Since the relatively large-sized material that cyclones handle is not as visible, cyclones are usually not equipped with opacity monitors. Excessive emissions of larger-sized particles can be detected by observing the area around a cyclone. Check the ground and equipment around the cyclone for deposition of material.

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

616.2 CYCLONE PHYSICAL CONDITIONS

Look around the cyclone and its ductwork and check its general condition. Look for corrosion, especially in the "cold spots" of units in corners of hoppers, near the solids discharge valve, and on access hatches. On positive pressure units look for fugitive emissions from corroded areas. In negative pressure units listen for air infiltration in corroded areas, warped access hatches, and eroded solids discharge valves.

616.3 SOLIDS DISCHARGE VALVE

For cyclones equipped with rotary discharge valves, flapper valves, or similar designs, make sure that the valve continuously moves and discharges solids to the screw conveyor or disposal area (as long as it can be inspected safely). If the cyclone is equipped with a pneumatic or pressurized hopper discharge system, check for the sound of the discharge valve operation. Unfortunately, the discharge operation may occur only after long intervals of time. The discharge frequency may vary between once every hour to once every eight hours.

Only allow facility personnel to open observation hatches on screw conveyors or dust storage/disposal containers. Wear protective goggles when this is done, especially if the cyclone is in operation. Respirators may also be necessary.

616.4 STATIC PRESSURE DROP

Find the pressure gauge for the unit and check the condition of the gauge to verify it will give an accurate reading. Some indications that the gauge may not be working properly include: the face of the gauge being covered with deposits, water or grime, and the gauge is in poor condition; or the gauge does not move when the process rate changes. If you are not sure if the gauge is working, ask facility personnel to disconnect one of the lines to the gauge to see if it responds.

If the gauge appears to be in good condition, record the pressure reading. Also record the time the reading was taken, especially if the process rate changes often. Correct the pressure reading with the baseline operating rate by using a form of the equation of state for an ideal gas:

600 SCRUBBERS

$$P_1 V_1 / T_1 = P_2 V_2 / T_2 \text{ and } P_2 = T_2 / V_2 [P_1 V_1 / T_1]$$

P_2 is the corrected pressure. This relationship can also be used to correct volume flow rates of ideal gases under actual i.e. (acfm) conditions to standard conditions i.e. (scfm). Volume flow rates would simply be substituted for the volume "V."

If the pressure drop is higher than the baseline value, there may be an accumulation of solids in the spinner vanes in a multi-cyclone. This will result in poor vortex formation and lower collection efficiency. If the pressure drop is lower than the baseline value, there could be erosion in the outlet tubes, excessive corrosion of the clean side tube sheet, or failure of the tube gaskets. These conditions can permit part of the gas stream to short circuit the collector, allowing a part of the gas stream to flow through the collector without being controlled.

If the pressure drop is not within the ranges stated on the Permit, it is a violation.

616.4.1 Level 3 and 4 Inspections

In level 3 and 4 inspections the pressure drop must be measured without the gauges on the control device. First, safe and convenient measurement ports must be located. In a level 4 inspection, these ports would have to be installed with the help of facility personnel (see Preferred Measurement Ports for Air Pollution Control Systems, EPA 340/1-86-034 regarding port installation). Ports may be found by disconnecting existing on-site gauges, but get facility personnel to remove the gauges.

If the ports are close together, connect the pressure gauge to them and measure the pressure for 1 to 5 minutes. If the ports are far apart, measure the static pressure at the port for 10 to 30 seconds and then measure the static pressure at the other port for the same amount of time. In order to get an accurate reading, the pressure measured at the ports should remain constant. The difference between the two values will yield the pressure drop.

**Table 616.1
CYCLONE INSPECTION FORM**

| <u>Pre-Inspection:</u> | <u>Field Inspection:</u> |
|---|---|
| Facility name: Unit I.D. number: | Date/time: |
| Permit number: Permit expiration date: | Inspector: Agency: |
| Facility address: | Facility contact person(s)/title(s): |
| Date unit was built or last modified: | |
| Cyclone General Physical Conditions | |
| Cyclone type/design: Large diameter cyclone, multi-cyclone, series of large diameter cyclones | Any visible emissions? Does the cyclone appear to be emitting water vapor? Is the body of the cyclone severely rusted or corroded? Any warped, poorly fitting hatches or accesses? Any excessive solids deposition on ground and surrounding equipment? |
| Solids Discharge Valve | |
| Permit requirements: | Is the solids discharge valve leaking any material or air? Is the discharge valve in good physical condition? |
| Pressure Drop, Temperature, O2 | |
| Min. pressure drop: Max. pressure drop: | Pressure drop: Temperature change: Change in O2 concentration: |
| Fan | |
| Fan rpm range: Fan current: | Fan rpm: Fan current: |

616.5 AIR INFILTRATION

Temperature measurements can be used to detect infiltration, but cyclones may not be equipped with temperature gauges. Large elaborate systems may be equipped with automatic temperature measurement devices that continually display temperature in a control room. Locate any existing temperature gauges on the inlet and outlet of the cyclone. If the gauges appear to be working and properly maintained, record the temperature. Compare the temperatures upstream and downstream of the cyclone with baseline values. In cyclones controlling exhaust from combustion processes, the temperature across the control devices should drop between 20 and 40°F. The drop in temperature will primarily depend on the gas flow rate and the adequacy of insulation. If the gas temperature drop is higher than normal, infiltration is very likely.

Very few cyclones are connected to oxygen monitors, but if it is connected to one, values that are higher than normal indicate air infiltration. Tests of oxygen levels are primarily limited to control devices handling waste streams from combustion sources. There should not be more than a 1% increase in the oxygen content of the gas across the cyclone.

616.5.1 Level 3 and 4 Inspections

For a level 3 inspection, an inspector's own instruments are used to measure inlet and outlet temperatures and other parameters. Suitable ports must be located; ports under .25 inches in diameter are usually sufficient. Make sure ports are relatively clean and free of deposits. For safety a grounding cable should be used, especially if the gas is explosive. While measurements are being taken, the probe must have a good seal with the duct so the reading will not be inaccurate from air infiltration. The oxygen and temperature measurements should be taken from the middle of the duct and the probe should be in the duct for several minutes before a reading is taken. For level 4 inspections, port locations must be found and drilled into the duct.

616.6 PROCESS INSPECTION

The processes equipped with cyclones to control emissions vary widely and the inspection of these processes may be very different, but there are some common items that can be checked.

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

The capture system should be checked for fugitive emissions and effectiveness. Record all applicable process operating rate parameters that illustrate that the process is operating according to Permit requirements. Some of the types of parameters that should be recorded include:

- Gas stream temperatures,
- Gas stream static pressures,
- Gas stream oxygen levels, and
- Raw material characteristics (do materials comply with Permits?).

617 CYCLONE PROBLEMS AND FAILURES

617.1 PLUGGING AND EROSION

Plugging can occur in the spinner vanes of a multi-cyclone; plugging is much less likely to occur in large diameter cyclones. An increase in the pressure drop at a given process operating rate is a good indication of pluggage in the system. A pressure drop that is lower than normal may indicate erosion in a cyclone. The most common areas of erosion are the gas outlet tubes and the spinner vanes. These areas are subjected to a lot of wear from moving particles. Another possible failure that can cause a decrease in the pressure drop is the failure of the gaskets on the clean side tube sheet. Corrosion in addition to erosion can create holes in a cyclone and wear down the spinner vanes. Plugging and erosion both lead to decreased collection efficiencies.

617.1.1 Plugged Discharge

Plugging of the cyclone discharge can be difficult to detect. The temperature across the cyclone and the pressure drop can remain unchanged even with a plugged discharge. Any accumulation of solids in the conical section of a cyclone will be reentrained in the exiting gas when it changes direction at the bottom and heads for the exit. The entrained particles will result in excess emissions, but since cyclones handle larger sized material, the emission may be difficult to see.

600 SCRUBBERS

Large diameter cyclones are often plugged by large or "stringy" substances which can cause a bridging of material in the unit. Operators may hammer on the cyclone to dislodge the material, but this practice may dent the cyclone or cause welds to fail if it is not done carefully. A dent can increase the possibility of solids accumulation and pluggage.

In high temperature applications a dry stream may become wet when the stream cools below its dewpoint, especially if the cyclone has little or no insulation. Wet material can increase the possibility of solids accumulation and pluggage.

Multi-cyclones are usually plugged at the solids outlet from overfilling of the hopper. Even after the hopper is emptied the cyclones will usually remain plugged.

The following are methods that can be used to avoid pluggage problems from the hopper:

- Design the hopper with an adequate slope
- Use an adequately sized hopper throat,
- Minimize internal obstacles which can lead to solids buildup
- Remove solids from the hopper frequently,
- Minimize air infiltration,
- Maintain solids discharge valves in good condition, and
- Maintain good insulation around hoppers.

617.2 AIR INFILTRATION

Air infiltration is a common problem for multi-cyclones that handle flue gas from boilers. The air infiltration is caused by thermal expansion and contraction from changing temperatures as the load on the boiler varies. High temperatures in the cyclone age the gaskets on the clean side tube sheet and can cause them to eventually leak. Air infiltration can disrupt the vortices in the cyclones and reentrain material from the hopper into the gas stream exiting the cyclones. Air infiltration can also lead to corrosion and deposits of solids in the cyclone.

The solids discharge area is a common area of air infiltration. The discharge area has high wear points, hatches, and may contain poke holes. Temperature drops in excess of 25°F are an indication of air infiltration.¹

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

617.3 CROSS-HOPPER GAS MOVEMENT

Cross-hopper gas movement is a condition more common in large multi-cyclones where the gas flow goes through the initial rows of cyclones, crosses the hopper through the dust discharge area, and exits through the cyclones toward the exit side of the device (Fig. 617.1). Another type of poor gas movement occurs when air flows through the multi-cyclone by flowing around the cyclones in the collector and out the exit.

The air in a cyclone follows the path of least resistance. The air follows a cross hopper path because the cyclones near the outlet are smaller and have a lower resistance to flow.

Cross-hopper gas movement has effects similar to air infiltration; it can cause particles to be reentrained into the cross-hopper flow from the hopper and result in excessive emissions.

Cross-hopper flow can sometimes be detected by the erosion pattern within the multi-cyclone. It can be prevented by putting gas flow restricting baffles in the multi-cyclone. Another possible means that can be used is to withdraw a portion of the air flow from the hopper area and send it to a separate control device.

617.4 PARTICLE BOUNCE

If the side walls of a cyclone are not smooth, particles can bounce and entrain into the inner vortex in the cyclone and get caught in the exiting gas stream. An accumulation of solids within the cyclone on the internal side walls can lead to particle bounce. Solids can accumulate from air infiltration. Air infiltration from the ambient air allows moisture to get into the cyclone and particles may stick on the side walls.

Dents in the cyclone from hammering on the cyclone can cause particle bounce. Creases in the cyclone can also cause particle bounce. Dents and creases may accidentally be created when a cyclone is erected.

**Solids
Accumulation**

Hammering

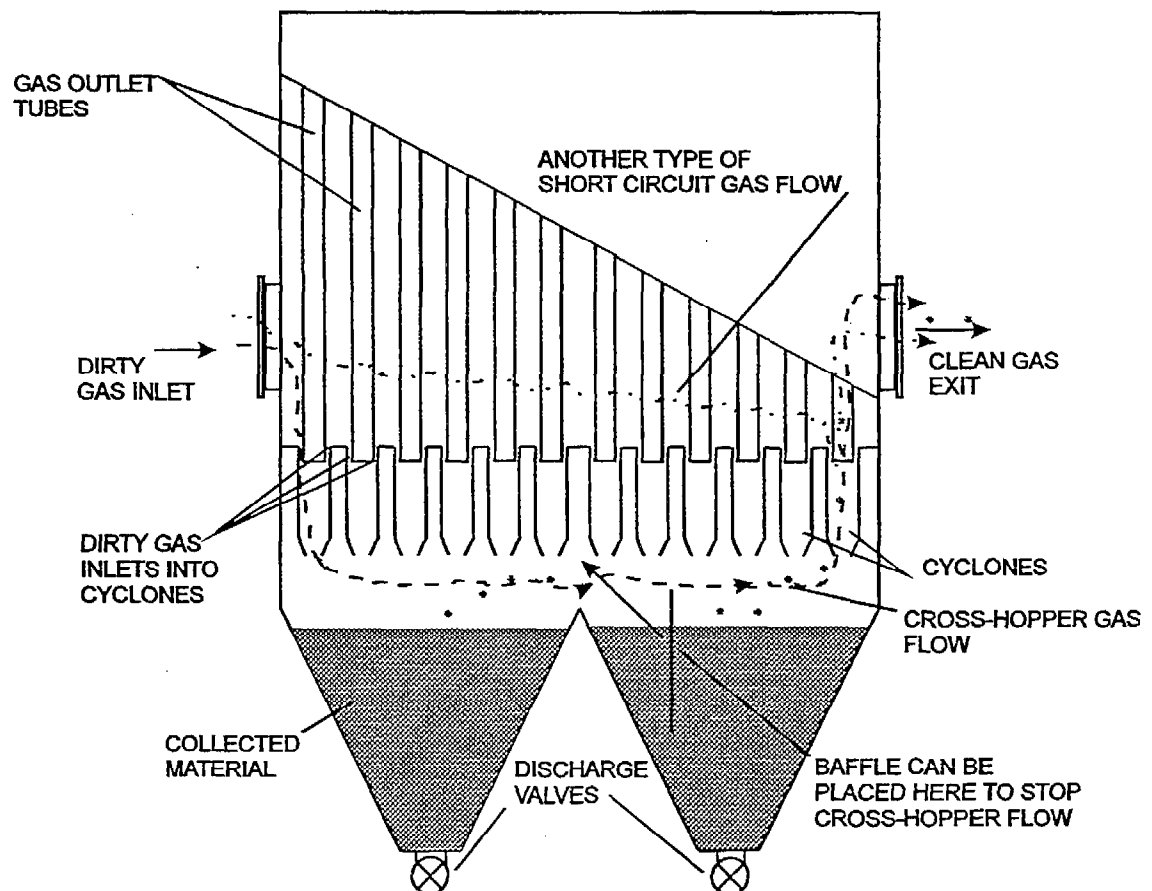


Figure 617.1 Cross-Hopper Gas Movement
in Multi-Cyclone

600 SCRUBBERS

VOC CONTROL DEVICES/ SCRUBBERS

617.5 GAS FLOW RATE

The efficiency of a cyclone is a function of the square of the velocity and also the flow rate. If the flow rate gets too low the efficiency will fall. Once the flow rate gets below 50% of the design flow rate, the particle removal efficiency will be significantly reduced.

Duct design can be one of the sources of an inadequate flow rate through a cyclone. Cyclone systems are sometimes designed with elbows (ductwork curves with 90° changes in direction) in the ductwork leading to the cyclone. The last elbow in the ductwork should be 6-8 duct diameters from the cyclone, so that the ductwork leading to the cyclone is straight. It may be necessary to have elbows near the inlet of the cyclone, but higher collection efficiencies are attained with a straight inlet duct.

Excessive flow rates over 120% of the design flow rate will also impair collection efficiency. High flow rates force vortices down the cyclone and increase turbulence in the air flow. Particles are entrained in the turbulent air patterns at the bottom of the cyclone.

618 POST-INSPECTION PROCEDURES

Prior to leaving the facility, the inspector should evaluate the compliance status of the plant and should have obtained all the information necessary to complete inspection forms.

The facility should be informed of the results of the inspection, advised of areas of concern where additional information or investigation is needed, or given a Notice of Violation (NOV) as soon as possible. Be prepared to make your compliance determinations, calculate excess emissions, and issue all necessary violation notices. Be able to document future NOVs which may be pending due to sample results or additional information requests. **All violations should be followed up**, consistent with your district policy, to ensure that the source is brought into compliance. Always update the Permit file with the actions that took place during and as a result of the inspection.

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APPENDIX A

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APPENDIX B

VOC Control
Devices/
Scrubbers

CALIFORNIA HEALTH AND SAFETY CODE (H&SC)

The following sections of the California Health and Safety Code listed below have been selected for verbatim presentation. **These H&SC sections are the basis for air pollution control laws, including the authority of districts to adopt and enforce regulations, to perform inspections, and to issue permits with conditions. (For specific situations, you may wish to consult the complete H&SC.)**

- 39000 Legislative Findings - Environment
- 39001 Legislative Findings - Agency Coordination
- 39002 Local and State Agency Responsibilities
- 39003 ARB Responsibilities
- 40000 Local / State Responsibilities
- 40001 Adoption and Enforcement of Rules and Regulations
- 40702 Adoption of Rules and Regulations
- 41509 No Limitation on Power to Abate Nuisance
- 41510 Right of Entry With Inspection Warrant
- 41700 No Person Shall Discharge Pollutants
- 41701 Opacity Standards - No Emissions Shall Exceed Ringelmann 2 . . .
- 42300 District Permit System
- 42301 Permit Issuance - Requirements
- 42301.6 Permit Approval: Powers and Duties of Air Pollution Control Officer
- 42301.7 Air Contaminants, Threatened Release
- 42303 Information Disclosure - Air Contaminant Discharge
- 42303.5 False Statements in Permit Applications
- 42304 Permit Suspension (Failure to Supply Information)
- 42352 Variance - Findings Required for Issuance
- 42400 Penalties, Criminal - Misdemeanor, \$1,000/Day and/or Six Months Jail
- 42400.1 Penalties, Criminal - Negligence, \$15,000/Day and/or Nine Months Jail
- 42400.2 Penalties, Criminal - Knowingly, \$25,000/Day and/or One Year Jail
- 42400.3 Penalties, Criminal - Willfully . . . \$50,000/Day and/or One Year Jail
- 42401 Penalties, Civil - Violating Order of Abatement \$25,000/Day
- 42402 Penalties, Civil - Violations . . . \$1,000/Day
- 42402.1 Penalties, Civil - Negligence, \$15,000/Day
- 42402.2 Penalties, Civil - Knowingly, \$25,000/Day
- 42402.3 Penalties, Civil - Willfully . . . \$50,000/Day
- 42402.5 Penalties, Civil - Administrative, \$500/Each Violation
- 42403 Penalties, Civil - Relevant Circumstances
- 42404.5 Statute of Limitations for Civil Actions
- 42450 Orders of Abatement, District Board: Authority, Notice, Hearing

H&SC
Sections
List

APPENDIX B

HEALTH AND SAFETY CODE, INTRODUCTION

The California Legislature passes laws, called statutes, that authorize Executive branch agencies (such as the Air Resources Board) to implement laws, through regulations, pursuant to the directives of the statutes.

The following relevant California H&SC references are included verbatim to provide you with the basis for California Air Pollution Control Laws. **The paragraph numbers are the H&SC Section numbers in numerical order:**

39000 LEGISLATIVE FINDINGS - ENVIRONMENT

H&SC
Sections in
Numerical
Order

The Legislature finds and declares that the people of the State of California have a primary interest in the quality of the physical environment in which they live, and that this physical environment is being degraded by the waste and refuse of civilization polluting the atmosphere, thereby creating a situation which is detrimental to the health, safety, welfare, and sense of well-being of the people of California.

39001 LEGISLATIVE FINDINGS - AGENCY COORDINATION

The Legislature, therefore, declares that this public interest shall be safeguarded by an intensive, coordinated state, regional, and local effort to protect and enhance the ambient air quality of the state. Since air pollution knows no political boundaries, the Legislature declares that a regional approach to the problem should be encouraged whenever possible and, to this end, the state is divided into air basins. The state should provide incentives for such regional strategies, respecting, when necessary, existing political boundaries.

39002 LOCAL AND STATE AGENCY RESPONSIBILITIES

Local and regional authorities have the primary responsibility for control of air pollution from all sources other than vehicular sources. The control of vehicular sources, except as otherwise provided in this division, shall be the responsibility of the State Air Resources Board. Except as otherwise provided in this division, including, but not limited to, Sections 41809, 41810, and 41904, local and regional authorities may establish stricter standards than those set by law or by the state board for nonvehicular sources. However, the state board shall, after holding public hearings as required in this division, undertake control activities

APPENDIX B

VOC Control Devices/ Scrubbers

in any area wherein it determines that the local or regional authority has failed to meet the responsibilities given to it by this division or by any other provision of law.

39003 ARB RESPONSIBILITIES

The State Air Resources Board is the state agency charged with coordinating efforts to attain and maintain ambient air quality standards, to conduct research into the causes of and solution to air pollution, and to systematically attack the serious problem caused by motor vehicles, which is the major source of air pollution in many areas of the state.

40000 LOCAL / STATE RESPONSIBILITIES

The Legislature finds and declares that local and regional authorities have the primary responsibility for control of air pollution from all sources, other than emissions from motor vehicles. The control of emissions from motor vehicles, except as otherwise provided in this division, shall be the responsibility of the state board.

40001 ADOPTION & ENFORCEMENT OF RULES / REGULATIONS

(a) Subject to the powers and duties of the state board, the districts shall adopt and enforce rules and regulations to achieve and maintain the state and federal ambient air quality standards in all areas affected by emission sources under their jurisdiction, and shall enforce all applicable provisions of state and federal law.

(b) The rules and regulations may, and at the request of the state board shall, provide for the prevention and abatement of air pollution episodes which, at intervals, cause discomfort or health risks to, or damage to property of, a significant number of persons or class of persons.

(c) Prior to adopting any rule or regulation to reduce criteria pollutants, a district shall determine that there is a problem that the proposed rule or regulation will alleviate and that the rule or regulation will promote the attainment or maintenance of state or federal ambient air quality standards.

**Prevent
and
Abate
Episodes**

APPENDIX B

40702 ADOPTION OF RULES AND REGULATIONS

A district shall adopt rules and regulations and do such acts as may be necessary or proper to execute the powers and duties granted to, and imposed upon, the district by this division and other statutory provisions. No order, rule, or regulation of any district shall, however, specify the design of equipment, type of construction, or particular method to be used in reducing the release of air contaminants from railroad locomotives.

41509 NO LIMITATION ON POWER TO ABATE NUISANCE

No provision of this division, or of any order, rule, or regulation of the state board or of any district, is a limitation on:

- (a) The power of any local or regional authority to declare, prohibit, or abate nuisances.
- (b) The power of the Attorney General, at the request of a local or regional authority, the state board, or upon his own motion, to bring an action in the name of the people of the State of California to enjoin any pollution or nuisance.
- (c) The power of a state agency in the enforcement or administration of any provision of law which it is specifically permitted or required to enforce or administer.
- (d) The right of any person to maintain at any time any appropriate action for relief against any private nuisance.

41510 RIGHT OF ENTRY WITH INSPECTION WARRANT

Right of Entry

For the purpose of enforcing or administering any state or local law, order, regulation, or rule relating to air pollution, the executive officer of the state board or any air pollution control officer having jurisdiction, or an authorized representative of such officer, upon presentation of his credentials or, if necessary under the circumstances, after obtaining an inspection warrant pursuant to Title 13 (commencing with Section 1822.50), Part 3 of the Code of Civil Procedure, shall have the right of entry to any premises on which an air pollution emission source is located for the purpose of inspecting such source, including

APPENDIX B

VOC Control Devices/ Scrubbers

securing samples of emissions therefrom, or any records required to be maintained in connection therewith by the state board or any district.

41700 NO PERSON SHALL DISCHARGE POLLUTANTS

Except as otherwise provided in Section 41705, no person shall discharge from any source whatsoever such quantities of air contaminants or other material which cause injury, detriment, nuisance, or annoyance to any considerable number of persons or to the public, or which endanger the comfort, repose, health, or safety of any such persons or the public, or which cause, or have a natural tendency to cause, injury or damage to business or property.

41701 OPACITY STANDARDS - NO EMISSIONS SHALL EXCEED RINGELMANN 2

Except as otherwise provided in Section 41704, or Article 2 (commencing with Section 41800) of this chapter other than Section 41812, or Article 2 (commencing with Section 42350) of Chapter 4, no person shall discharge into the atmosphere from any source whatsoever any air contaminant, other than uncombined water vapor, for a period or periods aggregating more than three minutes in any one hour which is:

(a) As dark or darker in shade as that designated as No. 2 on the Ringelmann Chart, as published by the United States Bureau of Mines, or

(b) Of such opacity as to obscure an observer's view to a degree equal to or greater than does smoke described in subdivision (a).

42300 DISTRICT PERMIT SYSTEM

(a) Every district board may establish, by regulation, a permit system that requires, except as otherwise provided in Section 42310, that before any person builds, erects, alters, replaces, operates, or uses any article, machine, equipment, or other contrivance which may cause the issuance of air contaminants, the person obtain a permit to do so from the air pollution control officer of the district.

(b) The regulations may provide that a permit shall be valid only for a specified period. However, the expiration date of any permit shall be extended upon

Opacity

APPENDIX B

completion of the annual review required pursuant to subdivision (e) of Section 42301 and payment of the fees required pursuant to Section 42311, unless the air pollution control officer or the hearing board has initiated action to suspend or revoke the permit pursuant to Section 42304, 42307, or 42390, that action has resulted in a final determination by the officer or the board to suspend or revoke the permit, and all appeals have been exhausted or the time for appeals from that final determination has been exhausted.

(c) The annual extension of a permit's expiration date pursuant to subdivision (b) does not constitute permit issuance, renewal, reopening, amendment, or any other action subject to the requirements specified in Title V.

42301 PERMIT ISSUANCE - REQUIREMENTS

**Permit System
Shall Do . . .**

A permit system established pursuant to Section 42300 shall do all of the following:

(a) Ensure that the article, machine, equipment, or contrivance for which the permit was issued does not prevent or interfere with the attainment or maintenance of any applicable air quality standard.

(b) Prohibit the issuance of a permit unless the air pollution control officer is satisfied, on the basis of criteria adopted by the district board, that the article, machine, equipment, or contrivance will comply with all of the following:

- (1) All applicable orders, rules, and regulations of the district and of the state board.
- (2) All applicable provisions of this division.

(c) Prohibit the issuance of a permit to a Title V source if the Administrator of the Environmental Protection Agency objects to its issuance in a timely manner as provided in Title V. This subdivision is not intended to provide any authority to the Environmental Protection Agency to object to the issuance of a permit other than that authority expressly granted by Title V.

(d) Provide that the air pollution control officer may issue to a Title V source a permit to operate or use if the owner or operator of the Title V source presents a variance exempting the owner or operator from Section 41701, any rule or regulation of the district, or any permit condition imposed pursuant to this

APPENDIX B

VOC Control Devices/ Scrubbers

section, or presents an abatement order that has the effect of a variance and that meets all of the requirements of this part pertaining to variances, and the requirements for the issuance of permits to operate are otherwise satisfied. The terms and conditions of any variance or abatement order may be incorporated into the permit as a compliance schedule, to the extent required by Title V.

(e) Require, upon annual renewal, that each permit be reviewed to determine that the permit conditions are adequate to ensure compliance with, and the enforceability of, district rules and regulations applicable to the article, machine, equipment, or contrivance for which the permit was issued which were in effect at the time the permit was issued or modified, or which have subsequently been adopted and made retroactively applicable to an existing article, machine, equipment, or contrivance, by the district board and, if the permit conditions are not consistent, require that the permit be revised to specify the permit conditions in accordance with all applicable rules and regulations.

(f) Provide for the reissuance or transfer of a permit to a new owner or operator of an article, machine, equipment, or contrivance. An application for transfer of ownership only, or change in operator only, of any article, machine, equipment, or contrivance which had a valid permit to operate within the two-year period immediately preceding the application is a temporary permit to operate. Issuance of the final permit to operate shall be conditional upon a determination by the district that the criteria specified in subdivisions (b) and (e) are met, if the permit was not surrendered as a condition to receiving emission reduction credits pursuant to banking or permitting rules of the district. However, under no circumstances shall the criteria specify that a change of ownership or operator alone is a basis for requiring more stringent emission controls or operating conditions than would otherwise apply to the article, machine, equipment, or contrivance.

42301.6 PERMIT APPROVAL: POWERS AND DUTIES OF AIR POLLUTION CONTROL OFFICER

(a) Prior to approving an application for a permit to construct or modify a source which emits hazardous air emissions, which source is located within 1,000 feet from the outer boundary of a schoolsite, the air pollution control officer shall prepare a public notice in which the proposed project or modification for which the application for a permit is made is fully described. The notice may be prepared whether or not the material is or would be subject to subdivi-

**Near a
Schoolsite**

APPENDIX B

Public
Comments
Considered

sion (a) of Section 25536, if the air pollution control officer determines and the administering agency concurs that hazardous air emissions of the material may result from an air release, as defined by Section 44303. The notice may be combined with any other notice on the project or permit which is required by law.

(b) The air pollution control officer shall, at the permit applicant's expense, distribute or mail the public notice to the parents or guardians of children enrolled in any school that is located within one-quarter mile of the source and to each address within a radius of 1,000 feet of the proposed new or modified source at least 30 days prior to the date final action on the application is to be taken by the officer. The officer shall review and consider all comments received during the 30 days after the notice is distributed, and shall include written responses to the comments in the permit application file prior to taking final action on the application.

(1) Notwithstanding Section 49073 of the Education Code, or any other provision of law, the information necessary to mail notices required by this section shall be made available by the school district to the air pollution control officer.

(2) Nothing in this subdivision precludes, at the discretion of the air pollution control officer and with permission of the school, the distribution of the notices to the children to be given to their parents or guardians.

(c) Notwithstanding subdivision (b), an air pollution control officer may require the applicant to distribute the notice if the district had such a rule in effect prior to January 1, 1989.

(d) The requirements for public notice pursuant to subdivision (b) or a district rule in effect prior to January 1, 1989, are fulfilled if the air pollution control officer or applicant responsible for giving the notice makes a good faith effort to follow the procedures prescribed by law for giving the notice, and, in these circumstances, failure of any person to receive the notice shall not affect the validity of any permit subsequently issued by the officer.

(e) Nothing in this section shall be deemed to limit any existing authority of any district.

APPENDIX B

VOC Control Devices/ Scrubbers

(f) An applicant for a permit shall certify whether the proposed source or modification is located within 1,000 feet of a schoolsite. Misrepresentation of this fact may result in the denial of a permit.

(g) The notice requirements of this section shall not apply if the air pollution control officer determines that the application to construct or modify a source will result in a reduction or equivalent amount of air contaminants, as defined in Section 39013, or which are hazardous air emissions.

(h) As used in this section:

(1) "Hazardous air emissions" means emissions into the ambient air of air contaminants which have been identified as a toxic air contaminant by the state board or by the air pollution control officer for the jurisdiction in which the project is located. As determined by the air pollution control officer, hazardous air emissions also means emissions into the ambient air from any substances identified in subdivisions (a) to (f), inclusive, of Section 44321 of the Health and Safety Code.

(2) "Acutely hazardous material" means any material defined pursuant to subdivision (a) of Section 25532.

Toxic Air Contaminant

42301.7 AIR CONTAMINANTS - THREATENED RELEASE

(a) If the air pollution control officer determines there is a reasonably foreseeable threat of a release of an air contaminant from a source within 1,000 feet of the boundary of a school that would result in a violation of Section 41700 and impact persons at the school, the officer shall, within 24 hours, notify the administering agency and the fire department having jurisdiction over the school.

(b) The administering agency may, in responding to a reasonably foreseeable threat of a release, do any of the following:

(1) Review the facility's risk management and prevention plan prepared pursuant to Section 25534 to determine whether the program should be modified, and, if so, require submission of appropriate modifications. Notwithstanding any other provision of law, the administering agency may order modification and implementation of a revised risk management and prevention plan at the earliest feasible date.

APPENDIX B

**Prevent,
Reduce,
Mitigate Injury**

(2) If the facility has not filed a risk management and prevention plan with the administering agency, require the preparation and submission of a plan to the administering agency pursuant to Section 25534. Notwithstanding any other provision of law, the administering agency may require the filing of a risk management and prevention plan and its implementation at the earliest feasible date.

(c) The air pollution control officer may, in responding to a reasonably foreseeable threat of a release, do any of the following:

(1) If necessary, issue an immediate order to prevent the release or mitigate the reasonably foreseeable threat of a release in violation of Section 41700 pending a hearing pursuant to Section 42450 when there is a substantial probability of an injury to persons at a school resulting from a release that makes it reasonably necessary to take immediate action to prevent, reduce, or mitigate that injury. The officer may not issue such an order unless there is written concurrence to issue the order by a representative of the administering agency.

(2) Apply to the district board for issuance of an order for abatement pursuant to Section 42450.

(d) Nothing in this section limits any existing authority of any district.

42303 INFORMATION DISCLOSURE - AIR CONTAMINANT DISCHARGE

An air pollution control officer, at any time, may require from an applicant for, or the holder of, any permit provided for by the regulations of the district board, such information, analyses, plans, or specifications which will disclose the nature, extent, quantity, or degree of air contaminants which are, or may be, discharged by the source for which the permit was issued or applied.

42303.5 FALSE STATEMENTS IN PERMIT APPLICATIONS

No person shall knowingly make any false statement in any application for a permit, or in any information, analyses, plans, or specifications submitted in conjunction with the application or at the request of the air pollution control officer.

APPENDIX B

VOC Control Devices/ Scrubbers

42304 PERMIT SUSPENSION (FAILURE TO SUPPLY INFORMATION)

If, within a reasonable time, the holder of any permit issued by a district board willfully fails and refuses to furnish the information, analyses, plans, or specifications requested by the district air pollution control officer, such officer may suspend the permit. Such officer shall serve notice in writing of such suspension and the reasons therefor on the permittee.

42352 VARIANCE - FINDINGS REQUIRED FOR ISSUANCE

(a) No variance shall be granted unless the hearing board makes **all** of the following findings:

(1) That the petitioner for a variance is, or will be, in violation of Section 41701 or of any rule, regulation, or order of the district.

(2) That, due to conditions beyond the reasonable control of the petitioner, requiring compliance would result in either (A) an arbitrary or unreasonable taking of property, or (B) the practical closing and elimination of a lawful business. In making those findings where the petitioner is a public agency, the hearing board shall consider whether or not requiring immediate compliance would impose an unreasonable burden upon an essential public service. For purposes of this paragraph, "essential public service" means a prison, detention facility, police or firefighting facility, school, health care facility, landfill gas control or processing facility, sewage treatment works, or water delivery operation, if owned and operated by a public agency.

(3) That the closing or taking would be without a corresponding benefit in reducing air contaminants.

(4) That the applicant for the variance has given consideration to curtailing operations of the source in lieu of obtaining a variance.

(5) During the period the variance is in effect, that the applicant will reduce excess emissions to the maximum extent feasible.

(6) During the period the variance is in effect, that the applicant will monitor or otherwise quantify emission levels from the source, if requested to do so by the district, and report these emission levels to the district pursuant to a schedule established by the district.

(b) As used in this section, "public agency" means any state agency, board, or commission, any county, city and county, city, regional agency, public district,

Variance
Conditions

Essential
Public
Service

APPENDIX B

or other political subdivision. [Further stipulations of Subsection 42352.5 are not included in this technical manual.]

42400 PENALTIES, CRIMINAL - MISDEMEANOR

(a) Except as otherwise provided in Section 42400.1, 42400.2, or 42400.3, any person who violates this part, or any rule, regulation, permit, or order of the state board or of a district, including a district hearing board, adopted pursuant to Part 1 (commencing with Section 39000) to Part 4 (commencing with Section 41500), inclusive, is guilty of a misdemeanor and is subject to a fine of not more than one thousand dollars (\$1,000) or imprisonment in the county jail for not more than six months, or both.

(b) If a violation under subdivision (a) with regard to the failure to operate a vapor recovery system on a gasoline cargo tank is directly caused by the actions of an employee under the supervision of, or of any independent contractor working for, any person subject to this part, the employee or independent contractor, as the case may be, causing the violation is guilty of a misdemeanor and is punishable as provided in subdivision (a). That liability shall not extend to the person employing the employee or retaining the independent contractor, unless that person is separately guilty of an action that violates this part.

(c) The recovery of civil penalties pursuant to Section 42402, 42402.1, 42402.2, or 42402.3 precludes prosecution pursuant to this section for the same offense. When a district refers a violation to a prosecuting agency, the filing of a criminal complaint is grounds requiring the dismissal of any civil action brought pursuant to this article for the same offense.

(d) Each day during any portion of which a violation of subdivision (a) occurs is a separate offense.

42400.1 PENALTIES, CRIMINAL - NEGLIGENCE

(a) Any person who negligently emits an air contaminant in violation of any provision of this part or any rule, regulation, permit, or order of the state board or of a district pertaining to emission regulations or limitations is guilty of a misdemeanor and is subject to a fine of not more than fifteen thousand dollars (\$15,000) or imprisonment in the county jail for not more than nine months, or both.

Each Day a
Separate
Offense

APPENDIX B

VOC Control Devices/ Scrubbers

(b) Any person who owns or operates any source of air contaminants in violation of Section 41700 which causes actual injury, as defined in paragraph (2) of subdivision (d) of Section 42400.2, to the health or safety of a considerable number of persons or the public is guilty of a misdemeanor and is punishable as provided in subdivision (a).

(c) Each day during any portion of which a violation occurs is a separate offense.

(d) The recovery of civil penalties pursuant to Section 42402, 42402.1, 42402.2, or 42402.3 precludes prosecution pursuant to this section for the same offense. When a district refers a violation to a prosecuting agency, the filing of a criminal complaint is grounds requiring the dismissal of any civil action brought pursuant to this article for the same offense.

42400.2 PENALTIES, CRIMINAL - KNOWINGLY, DOCUMENT FALSIFICATION / FAILURE TO TAKE CORRECTIVE ACTION

(a) Any person who emits an air contaminant in violation of any provision of this part, or any order, rule, regulation, or permit of the state board or of a district pertaining to emission regulations or limitations, and who knew of the emission and failed to take corrective action within a reasonable period of time under the circumstances, is guilty of a misdemeanor and is subject to a fine of not more than twenty-five thousand dollars (\$25,000) or imprisonment in the county jail for not more than one year, or both.

(b) For purposes of this section, "corrective action" means the termination of the emission violation or the grant of a variance from the applicable order, rule, regulation, or permit pursuant to Article 2 (commencing with Section 42350). If a district regulation regarding process upsets or equipment breakdowns would allow continued operation of equipment which is emitting air contaminants in excess of allowable limits, compliance with that regulation is deemed to be corrective action.

(c) Any person who, knowingly and with intent to deceive, falsifies any document required to be kept pursuant to any provision of this part, or any rule, regulation, permit, or order of the state board or of a district, is guilty of a misdemeanor and is punishable as provided in subdivision (a).

Corrective Action

APPENDIX B

(d) (1) Any person who owns or operates any source of air contaminants in violation of Section 41700 which causes actual injury to the health or safety of a considerable number of persons or the public, and who knew of the emission and failed to take corrective action within a reasonable period of time under the circumstances, is guilty of a misdemeanor and is punishable as provided in subdivision (a).

(2) As used in this subdivision, "actual injury" means any physical injury which, in the opinion of a licensed physician and surgeon, requires medical treatment involving more than a physical examination.

(e) Each day during any portion of which a violation occurs constitutes a separate offense.

(f) The recovery of civil penalties pursuant to Section 42402, 42402.1, 42402.2, or 42402.3 precludes prosecution pursuant to this section for the same offense. When a district refers a violation to a prosecuting agency, the filing of a criminal complaint is grounds requiring the dismissal of any civil action brought pursuant to this article for the same offense.

42400.3 PENALTIES, CRIMINAL - WILLFULLY, INTENTIONALLY

(a) Any person who willfully and intentionally emits an air contaminant in violation of any provision of this part or any rule, regulation, permit, or order of the state board or of a district, pertaining to emission regulations or limitations is guilty of a misdemeanor and is subject to a fine of not more than fifty thousand dollars (\$50,000) or imprisonment in the county jail for not more than one year, or both.

(b) The recovery of civil penalties pursuant to Section 42402, 42402.1, 42402.2, or 42402.3 precludes prosecution pursuant to this section for the same offense. When a district refers a violation to a prosecuting agency, the filing of a criminal complaint is grounds requiring the dismissal of any civil action brought pursuant to this article for the same offense.

(c) Each day during any portion of which a violation occurs constitutes a separate offense.

APPENDIX B

VOC Control Devices/ Scrubbers

42401 PENALTIES, CIVIL - VIOLATING ORDER OF ABATEMENT

Any person who intentionally or negligently violates any order of abatement issued by a district pursuant to Section 42450, by a hearing board pursuant to Section 42451, or by the state board pursuant to Section 41505 is liable for a civil penalty of not more than twenty-five thousand dollars (\$25,000) for each day in which the violation occurs.

42402 PENALTIES, CIVIL - GENERAL VIOLATIONS

(a) Except as otherwise provided in subdivision (b) or in Section 42402.1, 42402.2, or 42402.3, any person who violates this part, any order issued pursuant to Section 42316, or any rule, regulation, permit, or order of a district, including a district hearing board, or of the state board issued pursuant to Part 1 (commencing with Section 39000) to Part 4 (commencing with Section 41500), inclusive, is strictly liable for a civil penalty of not more than one thousand dollars (\$1,000).

(b) (1) Any person who violates any provision of this part, any order issued pursuant to Section 42316, or any rule, regulation, permit, or order of a district, including a district hearing board, or of the state board issued pursuant to Part 1 (commencing with Section 39000) to Part 4 (commencing with Section 41500), inclusive, is strictly liable for a civil penalty of not more than ten thousand dollars (\$10,000).

(2) Where a civil penalty in excess of one thousand dollars (\$1,000) for each day in which the violation occurs is sought, there is no liability under this subdivision if the person accused of the violation alleges by affirmative defense and establishes that the violation was caused by an act which was not the result of intentional or negligent conduct. In a district in which a Title V permit program has been fully approved, this paragraph shall not apply to a violation of federally enforceable requirements that occurs at a Title V source.

(c) Each day during any portion of which a violation occurs is a separate offense.

42402.1 PENALTIES, CIVIL - NEGLIGENCE OR ACTUAL INJURY

(a) Any person who negligently emits an air contaminant in violation of this part or any rule, regulation, permit, or order of the state board or of a district

Owner or
Operator is
Liable

pertaining to emission regulations or limitations is liable for a civil penalty of not more than fifteen thousand dollars (\$15,000).

(b) Any person who owns or operates any source of air contaminants in violation of Section 41700 which causes actual injury, as defined in paragraph (2) of subdivision (d) of Section 42400.2, to the health or safety of a considerable number of persons or the public is liable for a civil penalty as provided in subdivision (a).

(c) Each day during any portion of which a violation occurs is a separate offense.

**42402.2 PENALTIES, CIVIL - KNOWINGLY, DOCUMENT
FALSIFICATION, FAILURE TO TAKE CORRECTIVE ACTION**

(a) Any person who emits an air contaminant in violation of any provision of this part, or any order, rule, regulation, or permit of the state board or of a district pertaining to emission regulations or limitations, and who knew of the emission and failed to take corrective action, as defined in subdivision (b) of Section 42400.2, within a reasonable period of time under the circumstances, is liable for a civil penalty, of not more than twenty-five thousand dollars (\$25,000).

(b) Any person who, knowingly and with intent to deceive, falsifies any document required to be kept pursuant to any provision of this part, or any rule, regulation, permit, or order of the state board or of a district, is subject to the same civil penalty as provided in subdivision (a).

(c) Any person who owns or operates any source of air contaminants in violation of Section 41700 which causes actual injury, as defined in paragraph (2) of subdivision (d) of Section 42400.2, to the health or safety of a considerable number of persons or the public, and who knew of the emission and failed to take corrective action, as defined in subdivision (b) of Section 42400.2, within a reasonable period of time under the circumstances, is subject to a civil penalty as provided in subdivision (a).

(d) Each day during any portion of which a violation occurs is a separate offense.

APPENDIX B

VOC Control
Devices/
Scrubbers

42402.3 PENALTIES, CIVIL - WILLFULLY AND INTENTIONALLY

(a) Any person who willfully and intentionally emits an air contaminant in violation of this part or any rule, regulation, permit, or order of the state board, or of a district, pertaining to emission regulations or limitations, is liable for a civil penalty of not more than fifty thousand dollars (\$50,000).

(b) Each day during any portion of which a violation occurs is a separate offense.

42402.5 PENALTIES, CIVIL - ADMINISTRATIVE

In addition to any civil and criminal penalties prescribed under this article, a district may impose administrative civil penalties for a violation of this part, or any order, permit, rule, or regulation of the state board or of a district, including a district hearing board, adopted pursuant to Part 1 (commencing with Section 39000) to Part 4 (commencing with Section 41500), inclusive, if the district board has adopted rules and regulations specifying procedures for the imposition and amounts of these penalties. No administrative civil penalty levied pursuant to this section may exceed five hundred dollars (\$500) for each violation. However, nothing in this section is intended to restrict the authority of a district to negotiate mutual settlements under any other penalty provisions of law which exceeds five hundred dollars (\$500).

42403 PENALTIES, CIVIL - RELEVANT CIRCUMSTANCES

(a) The civil penalties prescribed in Sections 39674, 42401, 42402, 42402.1, 42402.2, and 42402.3 shall be assessed and recovered in a civil action brought in the name of the people of the State of California by the Attorney General, by any district attorney, or by the attorney for any district in which the violation occurs in any court of competent jurisdiction.

(b) In determining the amount assessed, the court, or in reaching any settlement, the district, shall take into consideration all relevant circumstances, including, but not limited to, the following:

- (1) The extent of harm caused by the violation.
- (2) The nature and persistence of the violation.
- (3) The length of time over which the violation occurs.

Civil Penalties
May Depend
On . . .

APPENDIX B

- (4) The frequency of past violations.
- (5) The record of maintenance.
- (6) The unproven or innovative nature of the control equipment.
- (7) Any action taken by the defendant, including the nature, extent, and time of response of the cleanup and construction undertaken, to mitigate the violation.
- (8) The financial burden to the defendant.

42404.5 STATUTE OF LIMITATIONS FOR CIVIL ACTIONS

Any limitation of time applicable to actions brought pursuant to Section 42403 shall not commence to run until the offense has been discovered, or could reasonably have been discovered.

42450 ORDERS OF ABATEMENT, DISTRICT BOARD: AUTHORITY, NOTICE AND HEARING

The district board may, after notice and a hearing, issue an order for abatement whenever it finds that any person is constructing or operating any article, machine, equipment, or other contrivance without a permit required by this part, or is in violation of Section 41700 or 41701 or of any order, rule, or regulation prohibiting or limiting the discharge of air contaminants into the air.

In holding such a hearing, the district board shall be vested with all the powers and duties of the hearing board. Notice shall be given, and the hearing shall be held, pursuant to Chapter 8 (commencing with Section 40800) of Part 3.

GLOSSARY

VOC Control
Devices/
Scrubbers

Absorption - An attraction exhibited between a liquid and a gas. The process of removing a soluble gas component from a gas mixture by dissolving the soluble gas in a liquid. Removing a gaseous pollutant by dissolving the pollutant in a liquid.

Activated Carbon - Carbon that has been processed to accentuate its adsorption properties. The process involves several heat treatments (also see pyrolysis). Activating carbon makes it porous, creating a large surface area for adsorption.

Adsorbate - The substance being adsorbed or collected on a solid surface. The adsorbate is usually a volatile, or gaseous substance.

Adsorbent - The solid medium providing an surface for adsorption. The solid is usually carbon.

Adsorption - An attraction exhibited between a solid and a gas, or a solid and a liquid when the solid and gas, or solid and liquid are in contact. The removal of a pollutant by attaching it to a solid.

Aerometric Diameter - A method of calculating the diameter of a particle, which is usually irregularly shaped, taking into account the particle's density. Particles with similar aerometric diameters behave similarly within a fluid (including air).

Afterburner - See thermal incinerator.

Airfoil - A curved surface, typically similar to the shape of a wing on an airplane.

Amine - Organic chemical used to absorb hydrogen sulfide (H_2S). Monoethanolamine (MEA) and diethanolamine (DEA) are common amines.¹⁵

Axial Fans - "Propeller" type fans or the common household type of fan. These types of fan are usually not used for most industrial applications. Axial fans can move large volumes of air, but cannot develop a large amount of static pressure.

Best Available Control Technology (BACT) - An emission limitation based on the maximum degree of emission reduction which (considering energy, environmental, and economic impacts and other costs) is achievable through

GLOSSARY

application of production processes and available methods, systems, and techniques. In no event does BACT permit emissions in excess of those allowed under any applicable NSPS or NESHAP. It is applicable on a case-by-case basis for each major new (or modified) emission source to be located in areas attaining the National Ambient Air Quality Standards. It applies to each pollutant regulated under the Federal Clean Air Act, and is concerned with Prevention of Significant Deterioration (PSD). See Sections 165(a) (4) and 169 of the Federal Clean Act.

Breakthrough - The time at which the mass transfer zone reaches the end of a carbon bed. At this time the hydrocarbon concentration exiting the carbon adsorber begins to increase.

Brine - A solution consisting primarily of salt and water. Brine has a specific gravity greater than 1.0 (The specific gravity of pure water is 1.0).

Brownian Displacement - A particle collection mechanism that affects extremely small particles. The kinetic energy of air molecules can cause very small particles to suddenly change direction and force the particles to impact a water droplet and be collected.

California Health and Safety Code (CH&SC) - A publication consisting of the state laws and statutes for air pollution control in California.

Carbon Dioxide (CO₂) - A gaseous product of combustion. Carbon dioxide is not considered to be a pollutant, but it is a greenhouse gas.

Carbonization - Destructive distillation. See pyrolysis.

Carbon Monoxide (CO) - A combustion product formed from incomplete combustion. It is a pollutant that forms when there is not enough oxygen or too much fuel in a combustion process. When inhaled, CO attaches more easily to hemoglobin than oxygen, reducing the amount of oxygen reaching the body's cells.

Catalytic Incinerator - A control device used to eliminate pollutants by means of oxidation using heat and a catalyst bed.

GLOSSARY

VOC Control Devices/ Scrubbers

Catalyst - A substance which hastens or retards a chemical reaction without undergoing a chemical change itself during the process.¹⁵

Catenary - A curve made by a flexible, uniform chain suspended between two points. A name used to describe Catenary Grid Scrubbers (a registered trademark of Otto York Co.) because of the shape of its trays.

Centrifugal Fan - The type of fan used for most industrial applications. These fans can develop high static pressures and flow rates. Centrifugal fans do not have propellers like axial fans; they typically have a rotating ring with a multitude of small blades.

Channeling - A problem that can occur in carbon adsorbers where solvent-laden air flows non-uniformly through the carbon bed. When channeling occurs, portions of a carbon bed receive more of a waste stream than others, causing parts of the bed to become saturated with VOCs or "used up." Excessive emissions can then result from VOCs passing through the bed through the saturated regions.

Chemical Adsorption - (Also called chemisorption or activated adsorption) Adsorption that occurs by means of a chemical reaction (as opposed to physical adsorption which occurs from van der Waals forces) With chemical adsorption the collected substances are generally unrecoverable.

Chevron - A type of mist elimination device in wet scrubbers made of zigzag baffles. Liquid droplets collect on the blades of a chevron and drain downward by gravity.

Chlorofluorocarbons (CFCs) - A group of compounds that has very useful industrial applications, but is detrimental to the ozone layer in the upper atmosphere of the Earth. CFCs are often used in air conditioners and refrigerators.

Clarifier - A device used to separate the solids out of scrubbing liquor by gravity.

Clean Gas Tube Sheet - The tube sheet on the outside surface of a multi-cyclone that is usually located near or at the top of the gas outlet tubes of the small diameter cyclones.

GLOSSARY

Combustion Particle Burnout - A mechanism where particulates form from combustion processes. Once the volatile material in a fuel vaporizes, the remaining incombustible material or ash can remain to become particulate matter in the exhaust.

Contact Condenser - A condenser where the cooling medium and the product being cooled are mixed together and brought into full contact. Contact condensers usually use water for the cooling medium.

Cooling Tower - A large louvered device over which water flows to cool and aerate the water. Although most cooling towers are rectangular in shape, some are cylindrical.¹⁵ As water flows down the device over the louvers, air is pulled upward. Some of the water evaporates and a water vapor plume may be seen emanating from the stack of the device. The water is cooled by the evaporation process.

Continuous Emission Monitor (CEM) - An instrument that continuously measures emissions. Hydrocarbons, sulfur dioxide and nitrogen oxides are pollutants often measured in stacks by continuous emission monitors.

Cyclone - A control device used to remove relatively large-sized particulates from a gas stream. A cyclone is cylindrically shaped and narrows toward the bottom. As a gas stream tangentially enters a cyclone it rotates rapidly in a cyclonic motion, forcing particulates out toward the wall of the device. Particulates hit the wall and slide down to the bottom of the device and the cleaned gas exits from the center of the cyclone at the top.

Cyclonic Demister - A cylindrically shaped demister vessel used to remove water droplets from a gas stream exiting a scrubber. Water droplets are removed by the cyclonic motion of the gas stream in the demister vessel. Water droplets are forced to the walls of the demister and drain down to the bottom by gravity.

Diffusiophoresis - A particle collection mechanism where imbalances in kinetic energy from collisions of different concentrations of molecules on different sides of a particle cause a particle to move toward the area of lower concentration.

GLOSSARY

VOC Control Devices/ Scrubbers

Dirty Gas Tube Sheet - The tube sheet on a multi-cyclone collector that connects the cyclones to the tube sheet. The dirty gas flows down through the tube sheet through the spinner vanes of the cyclones.

Droplet Evaporation - A particle formation mechanism where particles are formed from the evaporation liquid droplets from a scrubber.

Dry Bulb Temperature - The temperature of dry air.

Dry Scrubbing - Any scrubbing process that produces a waste containing less than 5% water.¹⁴ The two common methods of dry scrubbing include spray drying and dry injection.

Electrostatic Attraction - A collection mechanism that involves using the electrical charges carried by particles for collection. Particles may be intentionally charged (this is called field charging) with an electrical field. An opposite charge will then attract the particles.

Electrostatic Precipitator (ESP) - A large control device used to remove particulates from a gas stream by charging particulates with a direct current corona as they come near negatively charged wires in the device. The particulates then collect on positively charged plates.

Feret's Diameter - The diameter of a particle (practically all particles are irregular in shape) that is found by measuring the maximum edge to edge distance.

Flue Gas Desulfurization (FGD) - The process of removing sulfur compounds from the flue gas (exhaust) of power plants, combustion processes, and other processes.

Fouling - A problem that reduces the effectiveness of carbon beds. Dust, sulfates and ash can "plug up" a carbon bed and reduce the sites available for VOCs to adsorb on the carbon.

Freon - One of the most common chlorofluorocarbons (CFCs). It is used in many air conditioners and refrigerators, and it is detrimental to the ozone layer in the upper atmosphere.

GLOSSARY

Fugitive Emissions - The escape of pollutant emissions into the atmosphere from man-made or natural sources. Some examples include emissions of VOCs from leaking storage tanks, valves, flanges, pumps and compressors at refineries or chemical plants; particulates from storage piles; or natural windblown dust.

Gas Outlet Tube - The tube on the top part of a cyclone through which the cleaned gas exits the device.

Heel - A term for the compounds remaining in the bed of an adsorber after regeneration.

Heterogeneous Nucleation - A particle formation mechanism where solid material nucleates or accumulates on the surfaces of previously formed particles. The temperature must be below the dew point temperature of the material for heterogeneous nucleation to occur.

Homogeneous Nucleation - A particle formation mechanism where vapor phase material nucleates or accumulates on the surfaces of previously formed particles. The temperature must be below the dew point temperature of the material for homogeneous nucleation to occur.

Hood - The widened entry portion of a duct where a dirty gas is captured by negative pressure.

Hydrocarbons - Organic compounds of hydrogen and carbon atoms. There is a vast number of these compounds. Some examples include: methane, butane, heptane, octane, benzene, etc. Emissions of volatile hydrocarbons into the atmosphere can lead to the formation of smog in the atmosphere.

Inertial Impaction - The main collection mechanism for wet scrubbers. In scrubbers, this collection mechanism occurs when the inertia of a particle from the motion of a gas stream causes the particle to impact a droplet. This collection mechanism is also very important for baghouses. Larger particles are easier to collect than smaller ones with this collection mechanism, since larger particles have a larger mass and increased inertia.

Lean - An air-fuel mixture that has a too much air or not enough fuel.

GLOSSARY

VOC Control Devices/ Scrubbers

Lower Explosive Limit (LEL) - The concentration at which a mixture of air and volatile compounds becomes flammable.

Macropores - A term relating to carbon pore size. Pores greater than 500 angstroms in diameter (1 angstrom = 1×10^{-10} meters).

Manometer - A device used to measure the relative or gage pressure inside a vessel. A manometer has a glass tube that contains water or mercury, measuring the pressure in inches of water or mercury.

Martin's Diameter - The diameter of a particle at which point the particle would be divided into two equal areas.

Masking - A problem that can occur with the catalyst of a catalytic incinerator. Materials in a waste stream can cover a catalyst over time and reduce its ability to oxidize compounds. Compounds must come in contact with the catalyst to be oxidized by it.

Mass Transfer Zone - The zone of a carbon bed that performs adsorption. When a bed is first brought on line, a carbon bed starts adsorbing compounds at the entry part of the adsorber. The mass transfer zone, which is usually about three inches long, moves down the carbon bed as it gets saturated with compounds.

Mechanical Dispersion - See "physical attrition."

Mesh Pad Mist Eliminator - A mist eliminator used for scrubbers that is made of a series of interlaced wires and fiber. Droplets collect on the fibers and drain downward by gravity.

Mesopores - A term relating to carbon pore size. Pores between 20 and 500 angstroms in diameter (1 angstrom = 1×10^{-10} meters).

Mist Elimination - The process of removing water droplets from the waste stream of a scrubber. Mist elimination is important since many of the water droplets contain collected particles and if droplets are not properly removed, particles can be reentrained into the air. Cyclonic vessels, chevrons and mesh pads are common mist elimination devices.

GLOSSARY

Molecular Weight - The relative weight of atoms or molecules. The weight of one mole of atoms or molecules, one mole being 6.02×10^{23} individual atoms or molecules. The molecular weight of carbon, for example, is 12.

Multi-Cyclone - A control device used to remove particulates from a gas stream. The device is composed of a large number of small diameter cyclones. Small units can have as few as 16 small diameter cyclones, large units may have several hundred. Multi-cyclones are more efficient at particulate removal than large diameter cyclones.

National Ambient Air Quality Standards (NAAQS) - National Ambient Air Quality Standards are developed by EPA pursuant to Section 109 of the Federal Clean Air Act. NAAQS exist for nitrogen oxides, sulfur oxides, particulate matter, ozone, and carbon monoxide.

National Emission Standards for Hazardous Air Pollutants (NESHAPS) - Federal standards for the emissions of toxic compounds.

Natural Gas - Gaseous hydrocarbons made of at least 80% methane and maybe some ethane, propane, and butane.

New Source Performance Standards (NSPS) - Federal regulations from the EPA for new or modified stationary sources. They are located in the Code of Federal Regulations Title 40 Part 60.

Nitrogen Oxides (NO_x) - A compound of a nitrogen atom and one or more oxygen atoms. These compounds are emissions of combustion processes and can lead to ozone formation (examples: NO = nitrogen oxide; NO₂ = nitrogen dioxide). Most of the NO_x from combustion processes is in the form of NO, but NO later forms into NO₂. NO₂ is much more harmful than NO.

Notice of Violation (NOV) - Document issued to a company for violating air pollution regulations.

Organic - Of or containing carbon.

GLOSSARY

VOC Control Devices/ Scrubbers

Ozone (O₃) - A colorless, odorless gas formed by chemical reactions between hydrocarbons, nitrogen oxides and sunlight that is irritating and damaging to humans, plants and animals. It is the main component of smog and is California's biggest air pollution problem.

Packed Column - A common type of absorber that typically consists of a vessel filled with packing and fitted with spray nozzles at the top of the vessel. Pollutant laden gas flows up the vessel while liquid cascades down, absorbing compounds.

Packing - Generally round or cylindrical objects that are put into an absorber to maximize the surface area available for absorption. Many different types of packings with different shapes and characteristics are available.

Partial Pressure - The pressure of a gas in a mixture of gases that would be exerted if the gas was by itself.

Particulates - Solid or liquid particles in the air. Smoke, for example, contains particulate matter. Particulates less than 10⁻⁶ m in diameter are also called PM10. Particles of this size and smaller are of greatest concern because they can easily pass deep into the lungs.

Permit to Operate - A document issued to the owner or operator of pollution generating or control equipment allowing, the owner to use the equipment in a manner to reduce emissions.

PH Scale - A scale ranging from 0 to 14 used to measure the acidity and alkalinity of a solution where 0 is the strongest acid, 14 is the strongest base and 7 is neutral. Numbers less than 7 indicate a solution of increasing acidity and numbers greater than 7 indicate a solution of increasing alkalinity.¹⁵

Physical Adsorption - The adsorption or condensation of a substance on a solid without chemically altering any of the substances. Adsorption by means of van der Waals forces.

Physical Attrition - A particle formation mechanism where particles are created by two objects rubbing together. Grinding, sanding, and crushing are examples of operations that produce particulates by physical attrition. Physical attrition usually produces larger or moderately sized particulates.

GLOSSARY

Plate Column - A cylindrical vessel consisting of a number of plates inside to promote absorption. Liquid is sprayed into the top of the vessel and flows down from tray to tray by gravity through downspouts. The dirty gas stream flows up the device through openings in the plates. Absorption occurs in the froth formed on top of each plate.

Plenum - An air duct. The main duct in a ventilation system.

Poisoning - A problem that can reduce the ability of a catalyst to oxidize the compounds in a catalytic incinerator. Some substances such as lead, sulfur, arsenic, mercury, and others may react with the catalyst and therefore "poison" it. Poisoning of a catalyst is usually irreversible.

Psychrometer - A device used to measure dry bulb and wet bulb temperature. It has two thermometers and a handle that allows a person to twirl the device in a rotational motion. The dry bulb thermometer looks like an ordinary thermometer, but the wet bulb thermometer has a gauze on the end. When a wet bulb measurement is taken, the gauze is wetted and the psychrometer is twirled.

Psychrometric Chart - A chart with a graphical representation of air and water vapor that contains the following parameters: dry bulb temperature, wet bulb temperature, specific volume, enthalpy, relative humidity, and humidity ratio. Once two parameters are known the others can be determined.

Pump - A device used to add energy to a fluid in order to move the fluid from one location to another. There are generally two types, positive displacement and kinetic.

Pyrolysis - A process where carbon is heated in several stages to activate it, to make it efficient for adsorption.

Reactive Organic Compound (ROC) - See "volatile organic compound."

Reactive Organic Gas (ROG) - A term used by the Air Resources Board that means the same as volatile organic compound (VOC), but it also includes ethane as a VOC. The EPA definition of VOC does not include ethane.

GLOSSARY

VOC Control Devices/ Scrubbers

Regeneration - The process of removing adsorbed compounds from the bed of an adsorber. A vacuum and/or heat are used to accomplish regeneration.

Residence Time - The amount of time that compounds are within the combustion chamber of an incinerator.

Rich - An air-fuel mixture that has too much fuel or not enough air.

Ringelmann Chart - A gray to black smoke scale published by the U.S. Bureau of Mines ranging from 0 to 5, where "5" is black smoke with 100% opacity, "4" is 80% opacity, "3" is 60% opacity, "2" is 40% opacity, and "1" is 20% opacity. "1" is the limit in most districts.

Scouring - A condition that can adversely affect a catalyst bed, caused by the movement of the hot gas stream through an incinerator, wearing down the catalyst over time. The catalyst in an incinerator is sometimes in the form of a coating, so once it wears off, parts of the bed may become useless.

Sintered - To create a bonded mass of particles that are fused together by pressure and heat below the melting point of the material.

Smog - A combination of the word "smoke" and "fog." Pollutants such as ozone, carbon monoxide, particulate matter, nitrogen oxides, and sulfur oxides make up smog.

Source Test - A test performed on pollution generating or control equipment to determine the emissions from it. Source tests may have to be conducted on equipment without continuous emission monitors to determine the emissions.

Space Velocity - A parameter which is the combined volume flow rate of the inlet gas stream into the catalyst bed of a catalytic oxidizer divided by the volume of the catalyst bed. The inlet stream includes the sum of the volume flow rate from the emission stream, supplemental fuel, and combustion air. The space velocity is the reciprocal of the residence time.

Spinner Vanes - Vanes at the entry of a small diameter cyclone that impart a cyclonic motion to the dirty gas stream entering the cyclone. Small diameter cyclones are part of a multi-cyclone collector.

GLOSSARY

Static Pressure - The pressure exerted by stationary air. The pressure energy of a fluid. Static pressure is usually measured in inches of water column.²

Sulfur Dioxide (SO₂) - A pollutant that comes from combustion processes using fuels with sulfur in them, oilfield operations, refining, and other industrial operations. It has a sharp, pungent smell.

Sulfur Oxides (SO_x) - Sulfur compounds SO₂, SO₃, etc. See "sulfur dioxide."

Surface Condenser - A condenser where the compounds being condensed and a coolant exchange energy across a solid surface. The most common type of condenser.

Thermal Aging - The gradual recrystallization of the noble metal catalyst materials from the high temperatures that the catalyst bed is continually exposed to. It is an unavoidable gradual deterioration of the catalyst.

Thermal Burnout - The volatilization of the compounds from the catalyst bed that make up the catalyst in an incinerator. It is caused by excessively high temperatures.

Thermal Incinerator - A control device that uses the heat from the combustion of an auxiliary fuel to oxidize the compounds in a waste gas.

Thermal Oxidizer - See "thermal incinerator."

Thermophoresis - A relatively weak particle collection mechanism where particles are moved and possibly collected by different temperatures on different sides of the particle. Molecules on the hot side of a particle will have more kinetic energy and more energy will be transferred to the particle from collisions with air molecules. This will cause the particle to move in the direction of the cooler side.

Van Der Waals - Attractive forces that exist between atoms or molecules because of the movement of electrons in molecules or atoms. The movement of electrons can cause one side of a molecule to acquire a charge, making it able to attract molecules of opposite charge.

GLOSSARY

VOC Control Devices/ Scrubbers

Vapor Pressure - The pressure exerted by a vapor that is in equilibrium with its liquid state.¹⁵

Variance - Permission given to a facility by an APCD or AQMD to legally pollute beyond regulated limits because of a breakdown or other condition.

Velocity Pressure - The pressure exerted due to the motion of an air stream.

Volatile - A substance that evaporates at a high rate at a low temperature.

Volatile Organic Compound (VOC) - Any compound with at least one carbon atom except:

methane,
carbon monoxide,
carbon dioxide,
carbonic acid,
metallic carbides,
metallic carbonates,
ammonium carbonate,
methylene chloride,
1,1,1 trichloroethane (methyl chloroform),
1,1,2 trichlorotrifluoroethane (CFC-113),
trichlorofluoromethane (CFC-11),
dichlorodifluoromethane (CFC-12),
dichlorotetrafluoroethane (CFC-114),
chloropentafluoroethane (CFC-115),
trifluoromethane (CFC-23),
HCFC-123 (dichlorotrifluoroethane),
HCFC-134a (tetrafluoroethane),
HCFC-141b (dichlorofluoroethane),
HCFC-142b (chlorodifluoroethane), and
chlorodifluoromethane (CFC-22).

The exact listing of compounds may vary. Some districts use the terms precursor or reactive organic compounds to denote VOC. As a note, many of these compounds which are listed as exempt compounds may contribute to upper atmosphere ozone destruction. Other exempt compounds are being investigated

GLOSSARY

as possible toxic air contaminants. Finally, carbon dioxide is considered to be a "greenhouse gas" which may contribute to global warming, and carbon monoxide is a primary pollutant.

Wet Bulb Temperature - The temperature indicated by a wet bulb thermometer on a psychrometer. The temperature of atmospheric air that has gone through an adiabatic saturation process (adiabatic means no heat transfer). Adiabatic saturation is the process that occurs when a psychrometer is twirled, causing the water in the gauze of the wet bulb thermometer to evaporate. The energy of evaporation comes from the atmospheric air.²

Wet Slurry Throwaway Scrubbing - A type of flue gas desulfurization system that uses a non-soluble reagent and produces a waste that is disposed of.

Wet Solution Throwaway Scrubbing - A type of flue gas desulfurization system that uses a soluble reagent and produces wastes that must be disposed of.

Wet Sulfur Producing Scrubbing - A type of flue gas desulfurization system that produces saleable sulfur.

Index

A

Absorption 300 - 1
Adsorbate 200 - 3
Adsorbent 200 - 3
Adsorption 200 - 1, 300 - 1
Afterburners 500 - 5
Agglomeration 600 - 16
Air Horsepower 100 - 17
Air Infiltration 600 - 114, 600 - 116
Air Resources Board 100 - 1
Atmospheric Pressure 100 - 11
Authority to Construct 200 - 43, 400 - 23, 500 -
24, 600 - 92
Axial Fans 100 - 11

B

Blowers 100 - 9
Boilers 500 - 19
Bottom Inlet Cyclone 600 - 50
Brake Horsepower 100 - 17
Breakdown Rules 100 - 23
Breakthrough 200 - 10
Brownian Displacement 600 - 13
Bubble Cap 300 - 15
Bubble Towers 300 - 13
Bubble-Plate Columns 300 - 13

C

California Air Resources Board 100 - 1
California Clean Air Act 100 - 2, 100 - 22
California Code of Regulations 100 - 21
California Environmental Protection Agency 100
- 1
California Health and Safety Code 100 - 21
Carbonization 200 - 5
Catalytic Incinerators 500 - 11
Catenary Grid Scrubbers 600 - 26
Centrifugal Fans 100 - 12
CFCs 400 - 9
Channeling 200 - 22, 200 - 29, 300 - 9
Chemisorption 200 - 4, 300 - 2
Chevrons 600 - 62
Clarifier 600 - 72
Code of Federal Regulations 100 - 20
Collision Scrubbers 600 - 42

Combustion 500 - 1
Compliance Assistance Program 100 - 1
Condensation 400 - 1, 600 - 16
Condensation Growth Scrubbers 600 - 44
Contact Condensers 400 - 3
Continuous Emission Monitor 200 - 50
Cooling Towers 600 - 72
Cyclone Theory 600 - 58
Cyclones 600 - 45
 air infiltration 600 - 116
 cross-hopper gas movement 600 - 117
 particle bounce 600 - 117
 plugging 600 - 115
 static pressure drop 600 - 59, 600 - 111
Cyclonic Demisters 600 - 62

D

Dampers 100 - 13
Desorption 200 - 16
Diffusion Charging 600 - 14
Diffusiophoresis 600 - 16
District Regulations 100 - 22, 200 - 40, 400 -
10, 400 - 16, 500 - 21, 600 - 83
Droplet Evaporation 600 - 9
Droplet Reentrainment 600 - 100
Dry Bulb Temperature 600 - 67
Dry Scrubbing 600 - 81

E

Ejector Venturi Scrubbers 600 - 43
Electrostatic Attraction 600 - 14, 600 - 34
Empirical Evaluation 600 - 75
EPA 100 - 20
Equation of State 100 - 18

F

Fans 100 - 9
Federal Clean Air Act Amendments 100 -
20, 400 - 9
Federal Regulations 100 - 20, 400 - 9
Feret's Diameter 600 - 5
Field Charging 600 - 14
Fin Fan 400 - 6
Flares 500 - 20
Flooded Bed Scrubber 600 - 32
Flue Gas Desulfurization (FGD) 600 - 77
Fluidized Bed Adsorber 200 - 32

Fouling 200 - 19, 200 - 29, 400 - 7
Fresh Zone 200 - 10
Froth Scrubbers 600 - 35

G

Gage Pressure 100 - 11
Gas Atomized Scrubbers 600 - 35
Gas Ejector Scrubbers 600 - 45
Gravitational Settling 600 - 15

H

HCFCs 400 - 9
Heel 200 - 10
Heterogeneous Nucleation 600 - 9
HFC-134a 400 - 10
Homogeneous Nucleation 600 - 9
Hoods 100 - 7
Hydrocarbons 500 - 2

I

Impaction 600 - 11
Impingement Scrubbers 600 - 26
Incinerators 500 - 1
Incomplete Combustion 500 - 3
Inspection and Maintenance (I&M) 200 - 45, 400 - 24, 500 - 27, 600 - 95
Inspections 200 - 47, 400 - 27, 500 - 29, 600 - 97
Interception 600 - 13

K

Kremser-Brown Souders Equation 300 - 17

L

Large Diameter Cyclones 600 - 49
Levels of Inspection 200 - 47, 400 - 26, 500 - 28, 600 - 96
Liquid-To-Gas Ratio 600 - 17
Liquor Turbidity 600 - 104
Lower Explosive Limit 500 - 5, 500 - 13

M

Martin's Diameter 600 - 5
Masking 500 - 17
Mass Transfer Zone 200 - 10
Mechanical Collectors 600 - 45

Mechanical Scrubbers 600 - 21
Mesh Pads 600 - 64
Mist Elimination 600 - 60
Modifications 200 - 43, 400 - 23, 500 - 24, 600 - 93
Montreal Protocol 400 - 9
Moving Bed Scrubbers 600 - 31
Multi-Cyclones 600 - 54

N

NESHAPS 100 - 20
Newton's Law 600 - 10, 600 - 49
Notice of Violation 100 - 22
NOx Rules 600 - 89
NSPS 100 - 20, 600 - 82

O

Odors 200 - 42, 400 - 22, 500 - 23, 600 - 92
Orifice Scrubbers 600 - 42
Ozone 100 - 5
Ozone Depleting Compound (ODC) 400 - 9
Ozone Depleting Potential (ODP) 400 - 8

P

Packed Column 300 - 5, 600 - 29
Packed Scrubbers 600 - 27
Packed Towers 300 - 5, 600 - 29
Packing 300 - 9, 300 - 10, 600 - 27
Partial Pressure 400 - 2
Particle Bounce 600 - 117
Particulate Matter 600 - 1
 collection mechanisms 600 - 10
 formation mechanisms 600 - 8
 shapes 600 - 5
 sizes 600 - 4
Particulate Matter Rules 600 - 85
Penetration Models 600 - 77
Permits to Operate 200 - 43, 200 - 47, 400 - 23, 400 - 27, 500 - 21, 500 - 24, 500 - 29, 600 - 92, 600 - 97
PH 600 - 74, 600 - 105
Physical Adsorption 200 - 1
Physical Attrition 600 - 8
Pilot Tests 600 - 76
Plate Columns 300 - 13
Poisoning 500 - 17

Porosity 200 - 6, 200 - 18
Pressure Drop 200 - 51, 400 - 30, 600 - 40, 600 - 59, 600 - 74, 600 - 101, 600 - 111
Psychrometer 600 - 67
Psychrometric Chart 600 - 67
Pumps 600 - 71
Pyrolysis 200 - 5

R

RECLAIM 200 - 42, 400 - 17, 500 - 22
Refrigerants 400 - 8
Regeneration 200 - 16, 200 - 19, 200 - 30
 Steaming 200 - 17, 200 - 19, 200 - 36
 Vacuum 200 - 17
Relative Humidity 200 - 27, 600 - 67
Residence Time 500 - 4, 500 - 19
Ringelmann Chart 600 - 84, 600 - 99
Rod Deck Scrubbers 600 - 41
Rotary Carbon Adsorber 200 - 32

S

Saturated Zone 200 - 10
Scouring 500 - 16
Scrubbers Plumes 600 - 66
Scrubbing Systems 600 - 17
Sieve Tray Scrubbers 600 - 26
Small Diameter Cyclone 600 - 54
Solids Discharge Valves 600 - 50, 600 - 111
Sorption 300 - 1
Spray Chambers 600 - 18
Spray Towers 600 - 19
Standard Temperature and Pressure (STP) 600 - 17
State Regulations 100 - 21, 400 - 9
Static Pressure 100 - 11
Steam Regeneration 200 - 36
Stoichiometric Combustion 500 - 3
Stoneware's Generalized Pressure Drop Correlation 300 - 16
Sulfur Dioxide Rules 600 - 89
Sulfur Producing Scrubbing 600 - 80
Surface Condensers 400 - 3

T

Thermal Aging 500 - 17
Thermal Burnout 500 - 17
Thermal Incinerator 500 - 5
Thermal Oxidizers 500 - 5
Thermophoresis 600 - 15
Three T's of Combustion 500 - 3
Timers and Monitors 200 - 22
Tray Tower Scrubbers 600 - 23
Tube Sheets 600 - 54

V

Van der Waals Forces 200 - 1, 600 - 11
Variance 100 - 25
Velocity Pressure 100 - 11, 100 - 16
Venturi Scrubbers 600 - 35
 pressure drop 600 - 40
Vertical Spray Rotor Scrubber 600 - 21
Visible Emissions 500 - 31, 600 - 83, 600 - 99, 600 - 110
Volatile Organic Compounds (VOCs) 100 - 4, 200 - 40, 400 - 16, 500 - 21

W

Water Vapor Plumes 600 - 66
Wellman-Lord Scrubbing System 600 - 81
Wet Bulb Temperature 600 - 67
Wet Ionizing Scrubber 600 - 34
Wet Slurry Throwaway Scrubbing 600 - 79
Wet Solution Throwaway Scrubbing 600 - 80
Woven Pad 600 - 65

